

# **Gluon Saturation at the Electron Ion Collider**

**Snowmass 2021 Energy Frontier Workshop - Restart**

**Björn Schenke, Brookhaven National Laboratory**

**with**

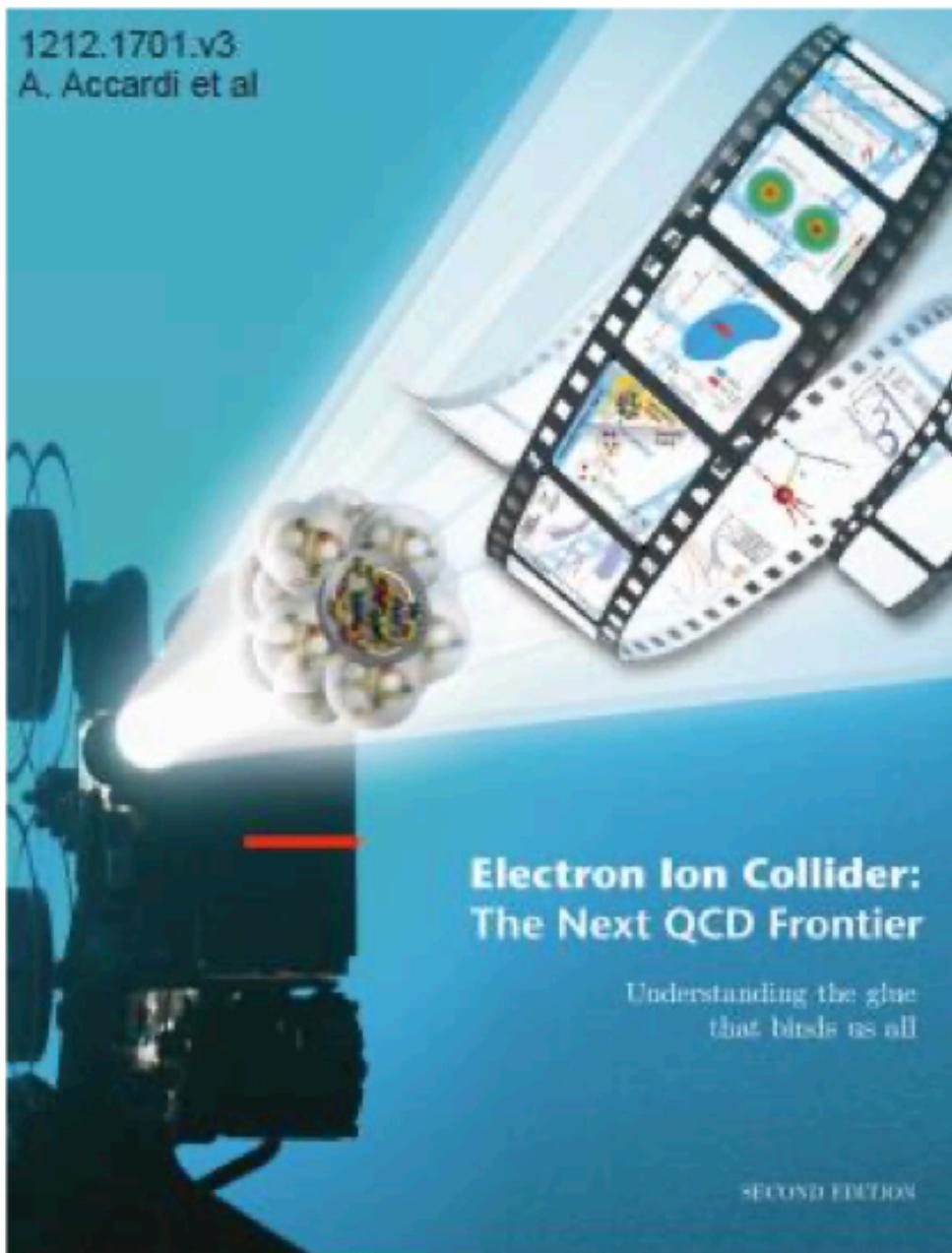
**Renaud Boussarie, Ecole Polytechnique, CPHT**

**Tuomas Lappi, University of Jyväskylä**

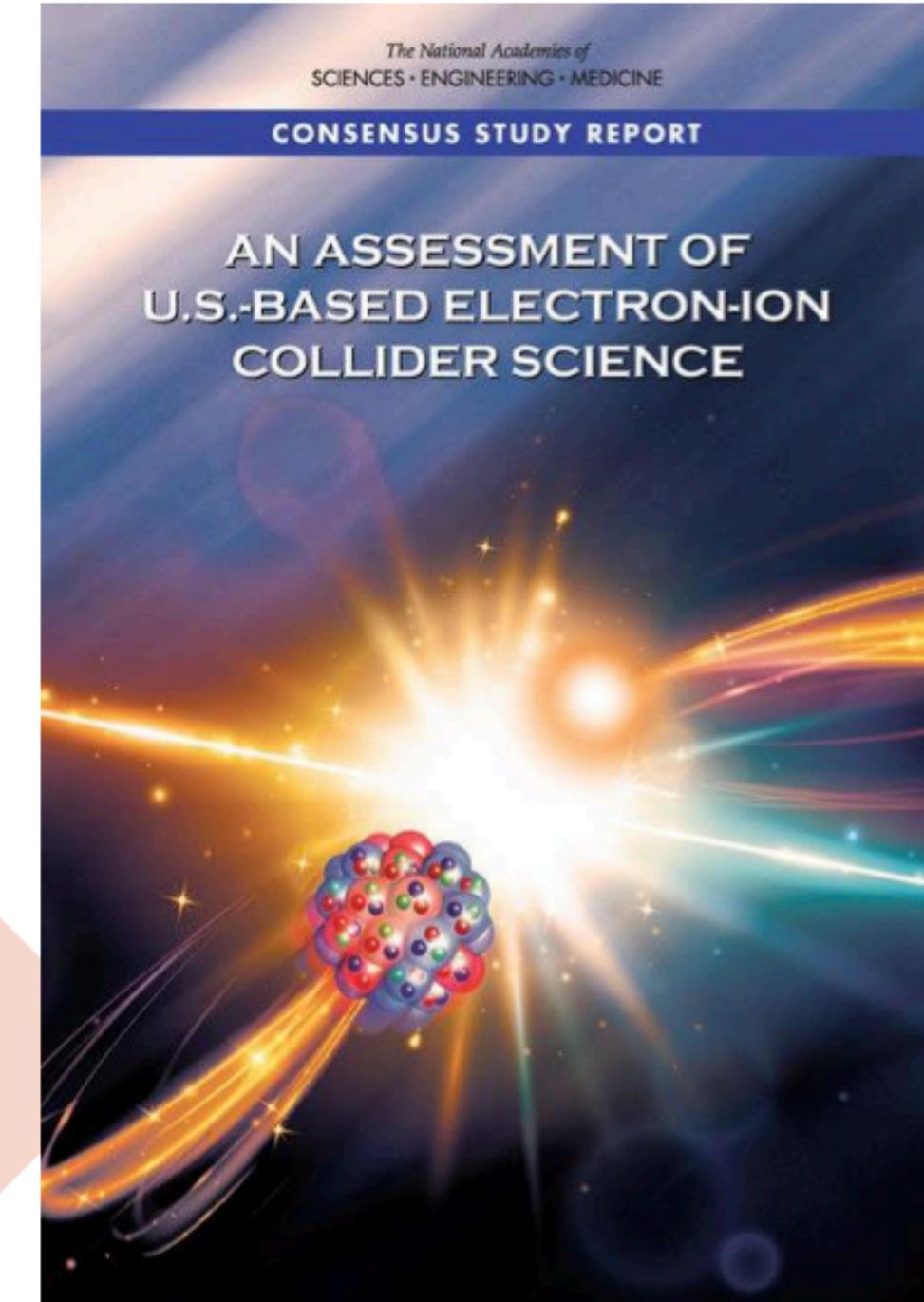
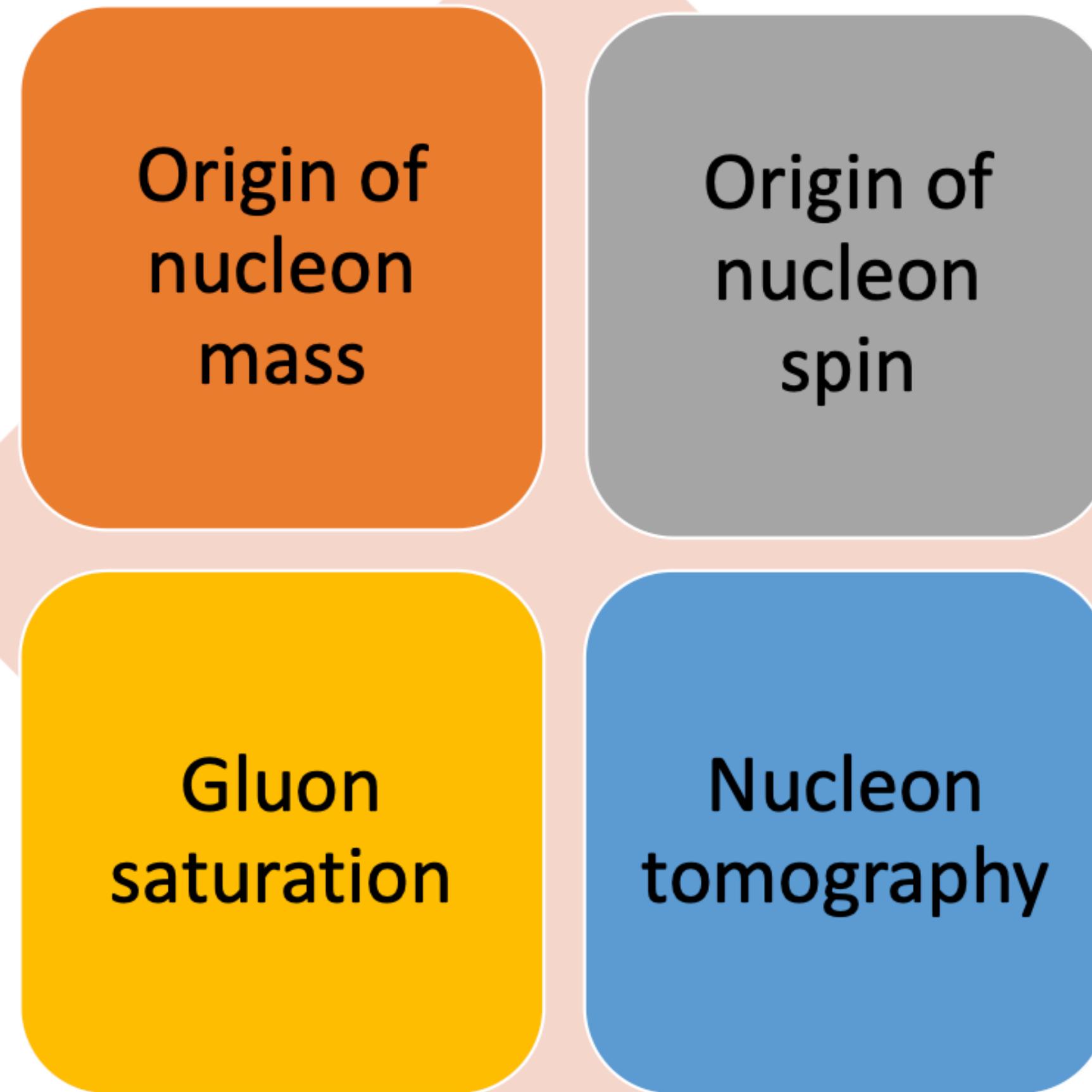
**Sören Schlichting, Bielefeld University**

**09/02/2021**

# Science goals of the Electron Ion Collider

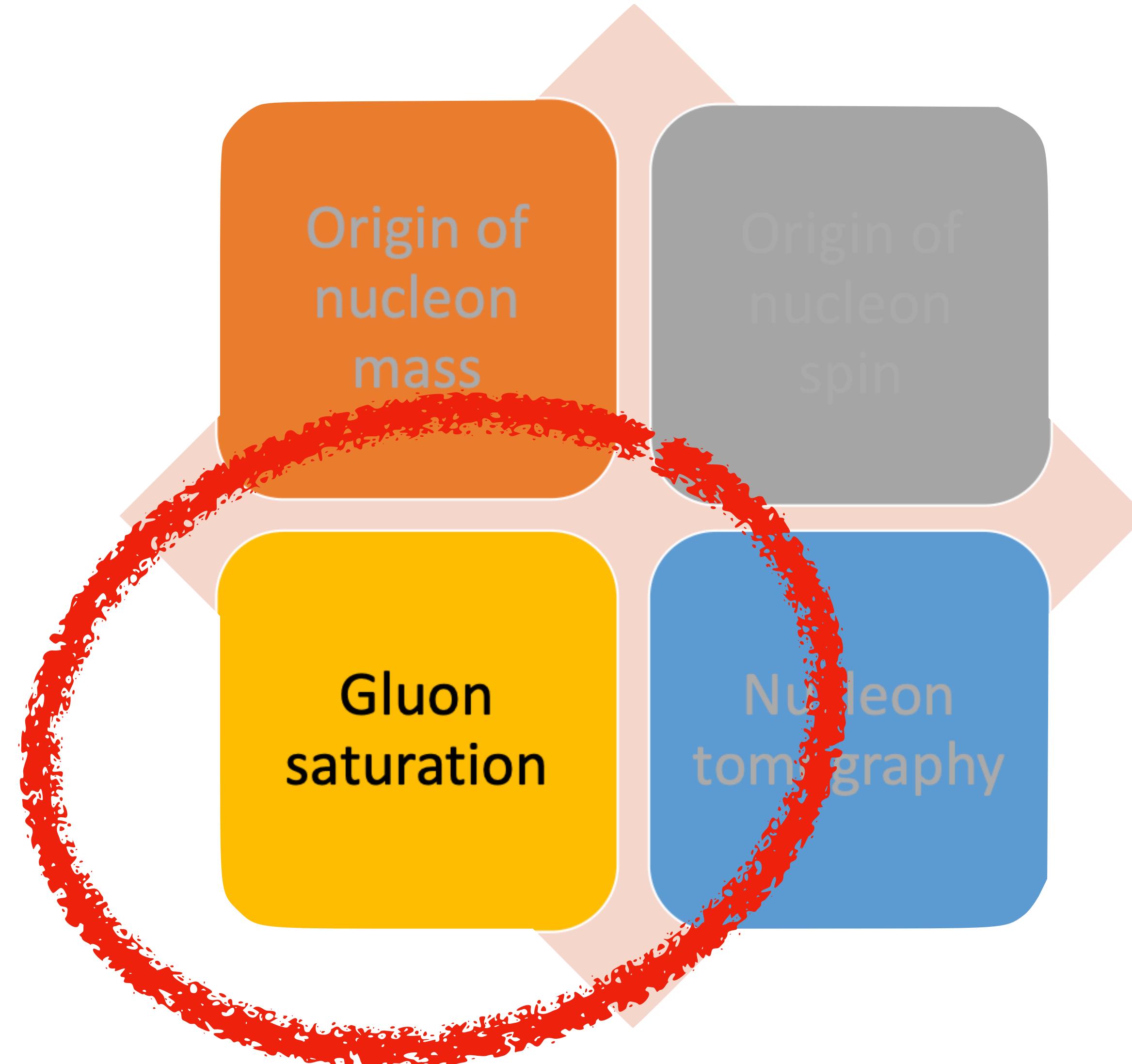


White paper  
arXiv:1212.1701

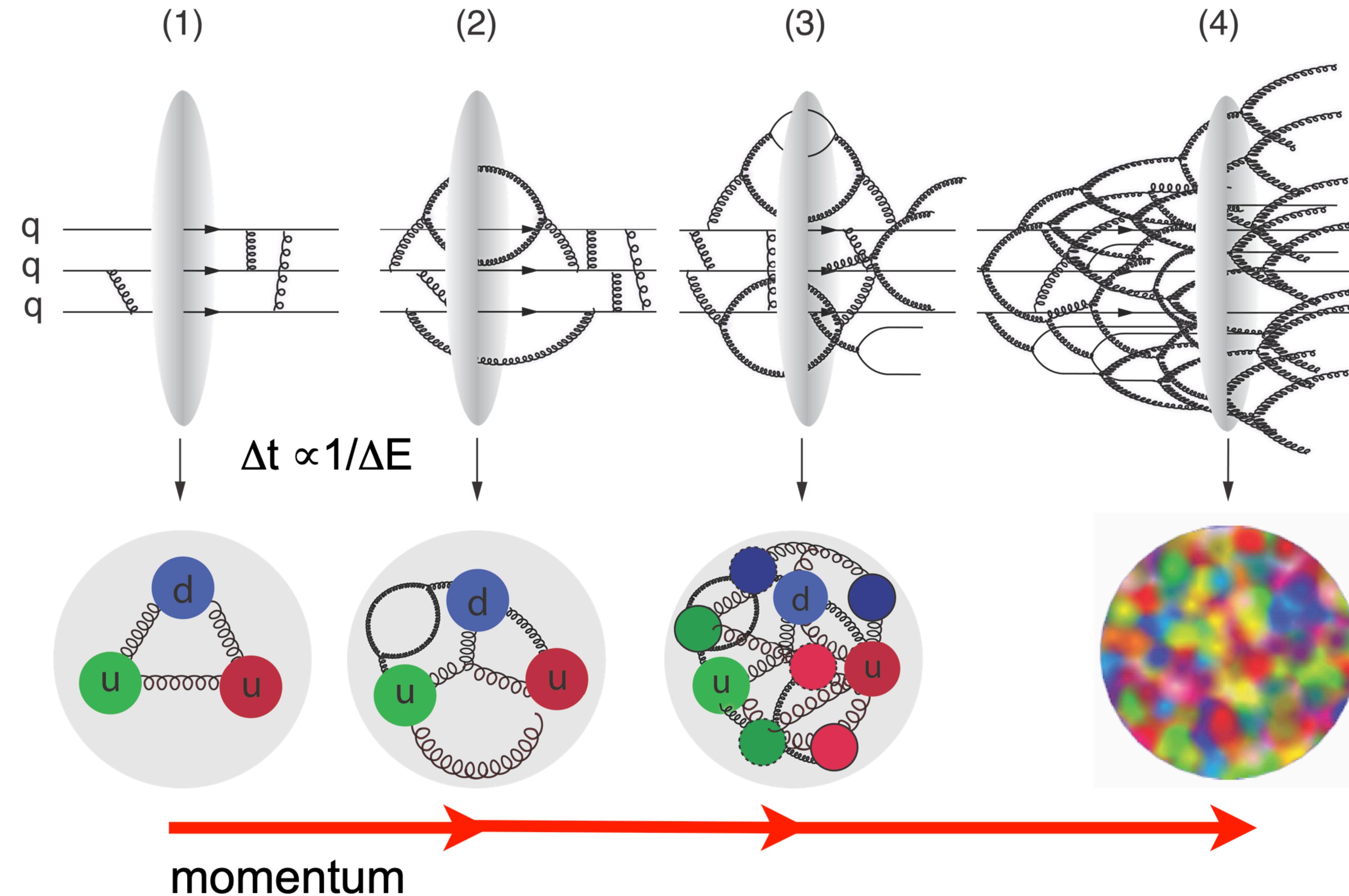


NAS report  
July 2018

# Science goals of the Electron Ion Collider



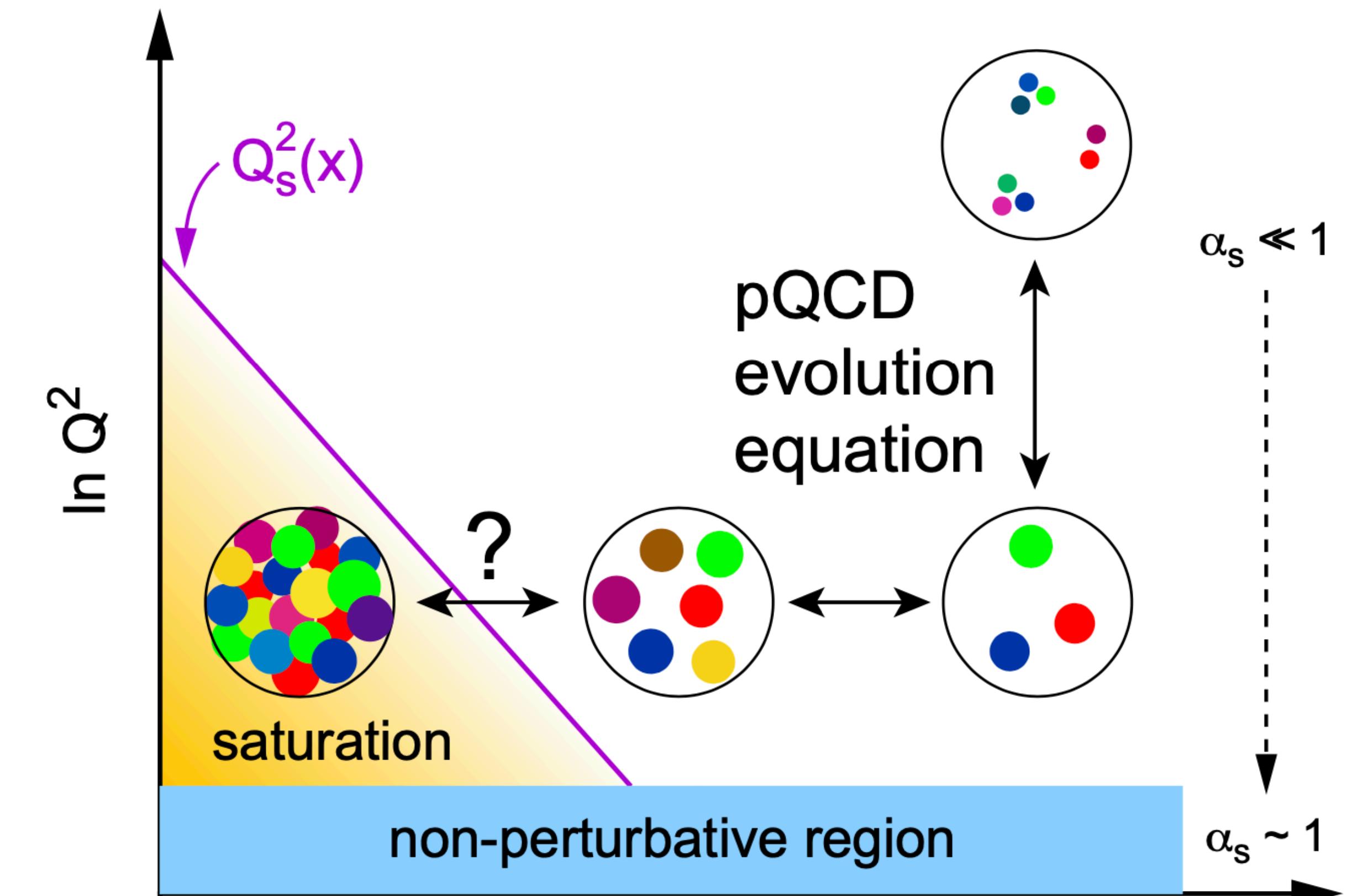
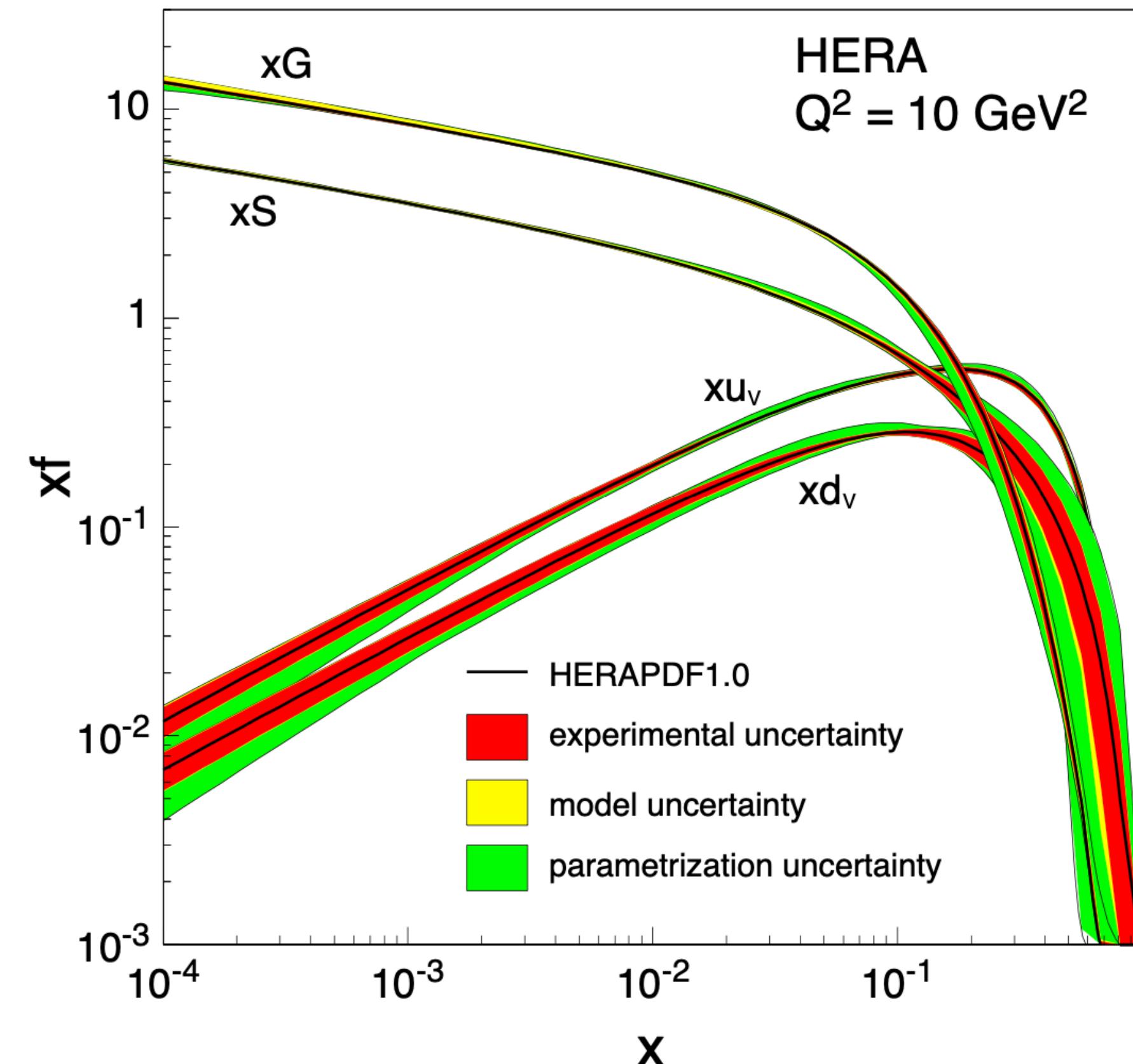
# The boosted proton



Artwork: T. Ullrich

# Saturation

Explosive growth of gluon density violates unitarity

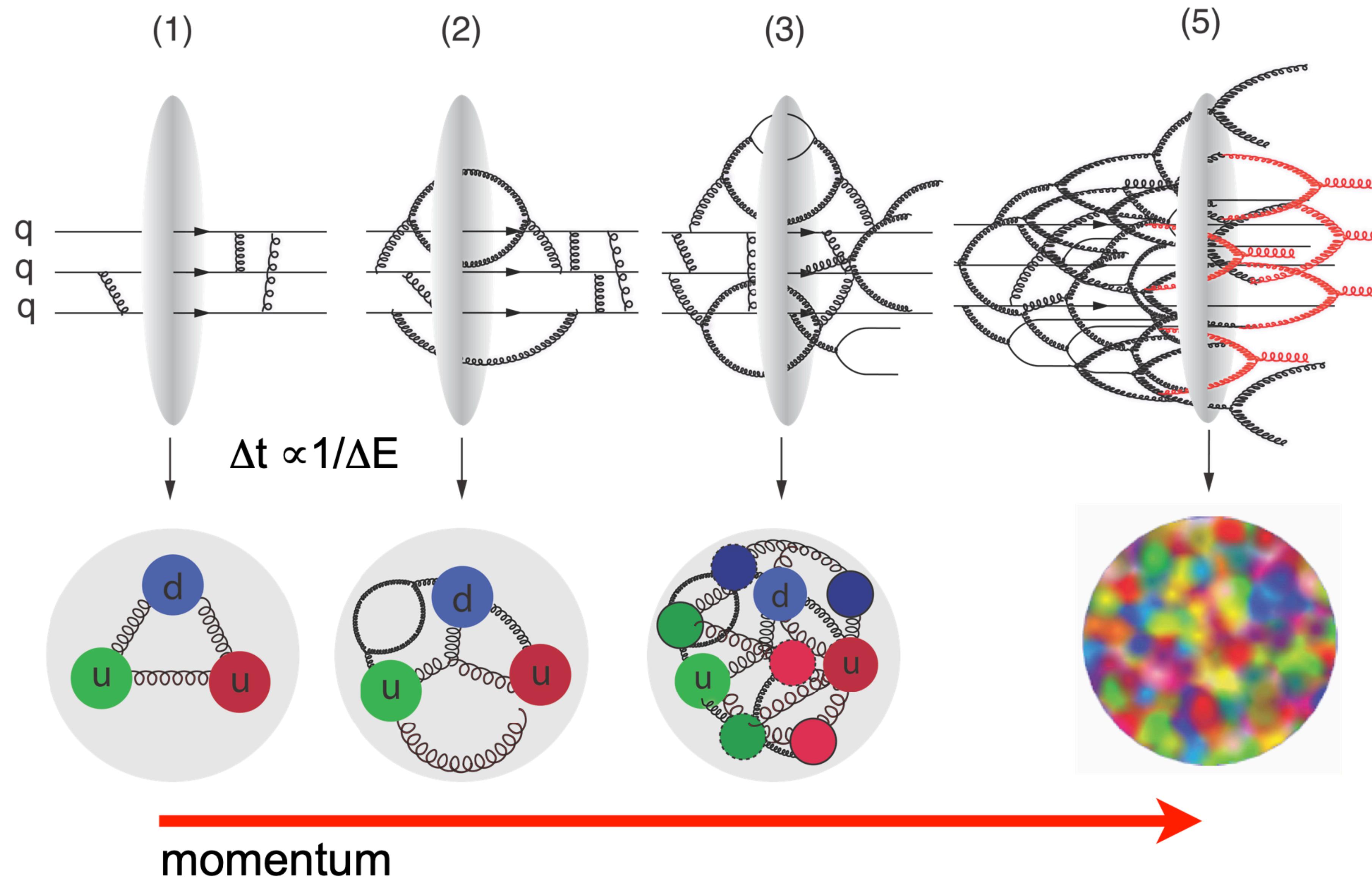


BUT: Recombination will balance gluon splittings

Need non-linear evolution equations at low  $x$  and low to moderate  $Q^2$

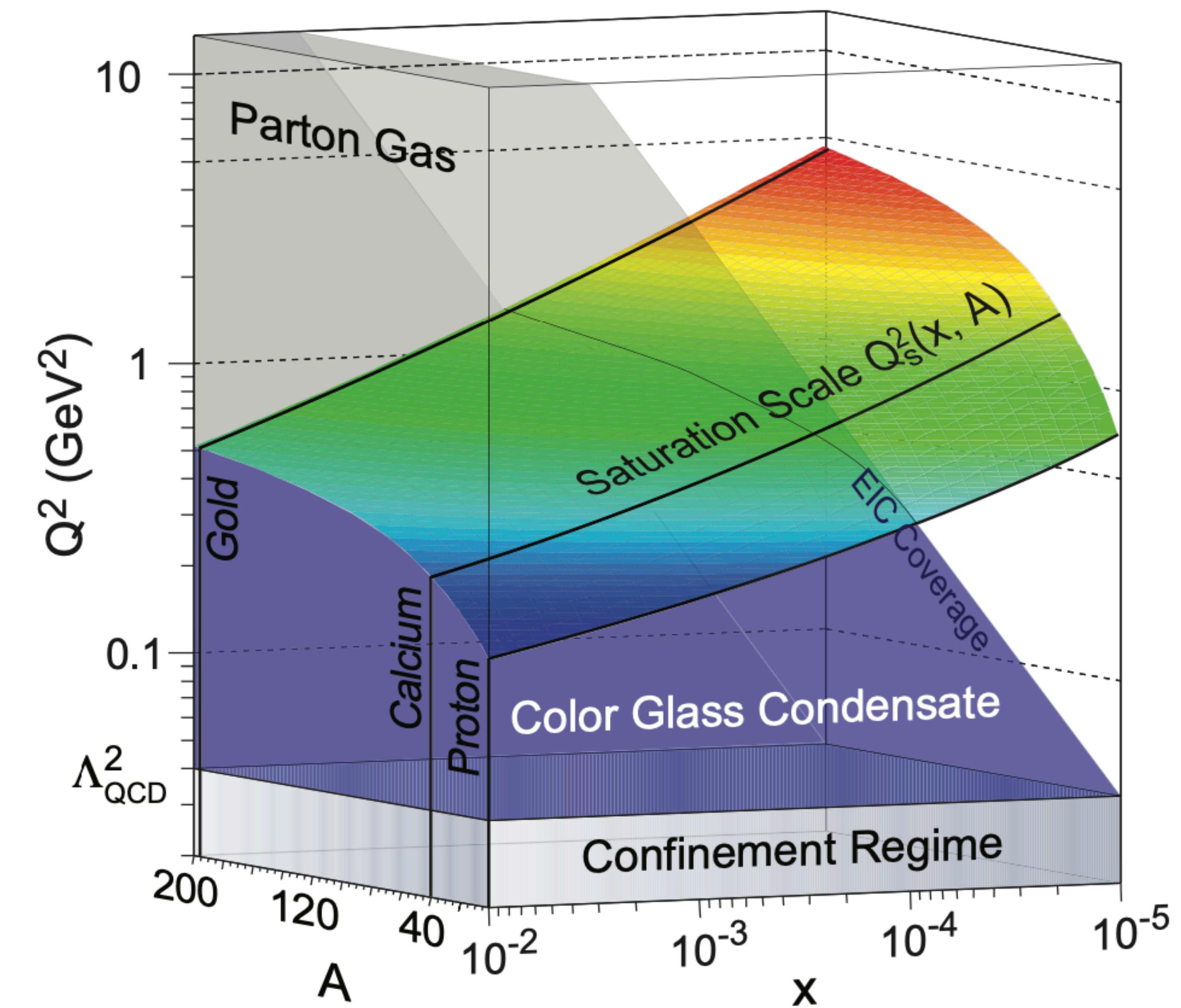
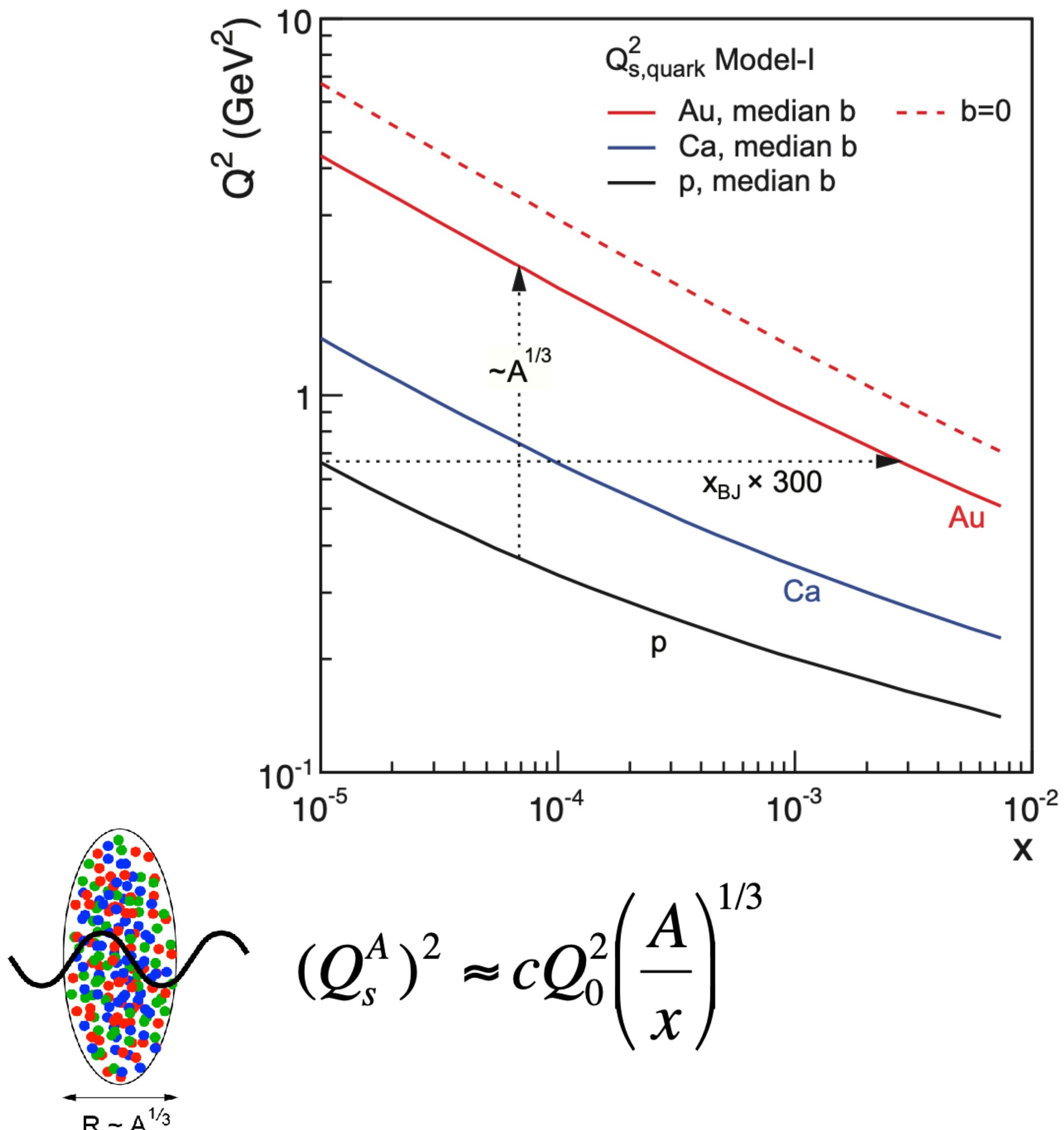
Saturation of gluon densities is characterized by the scale  $Q_s(x)$

# The boosted proton



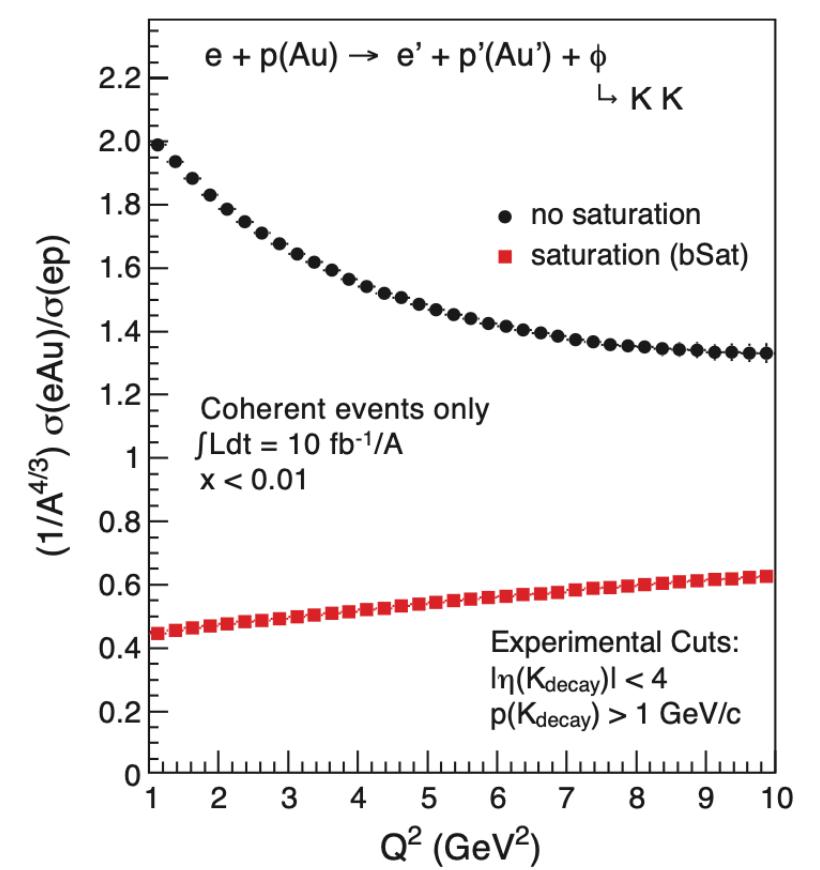
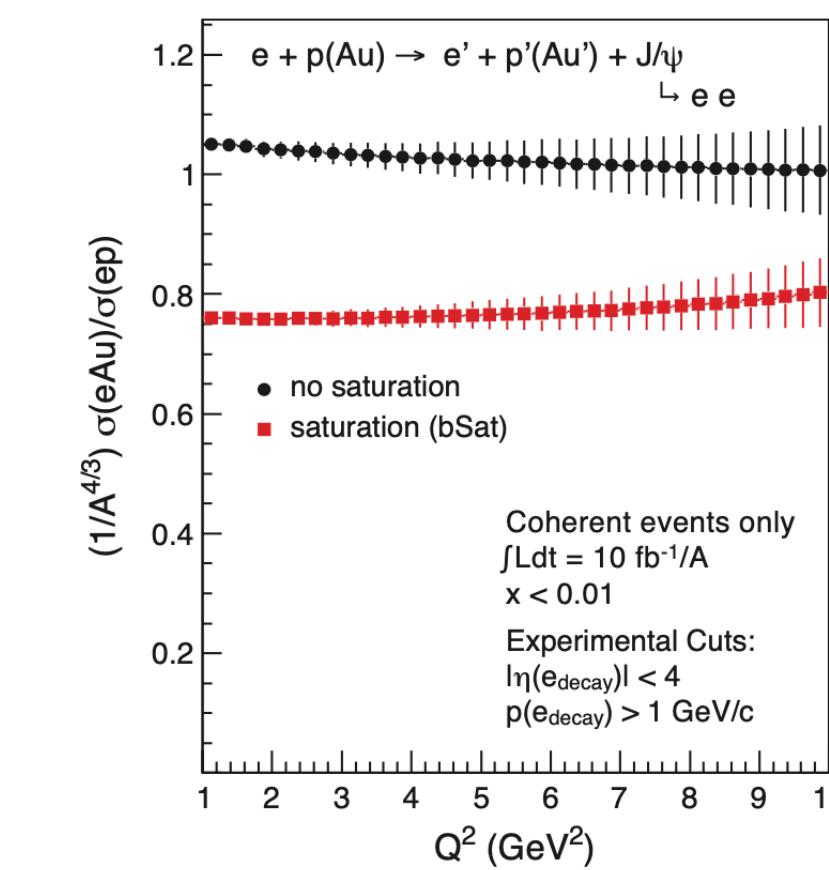
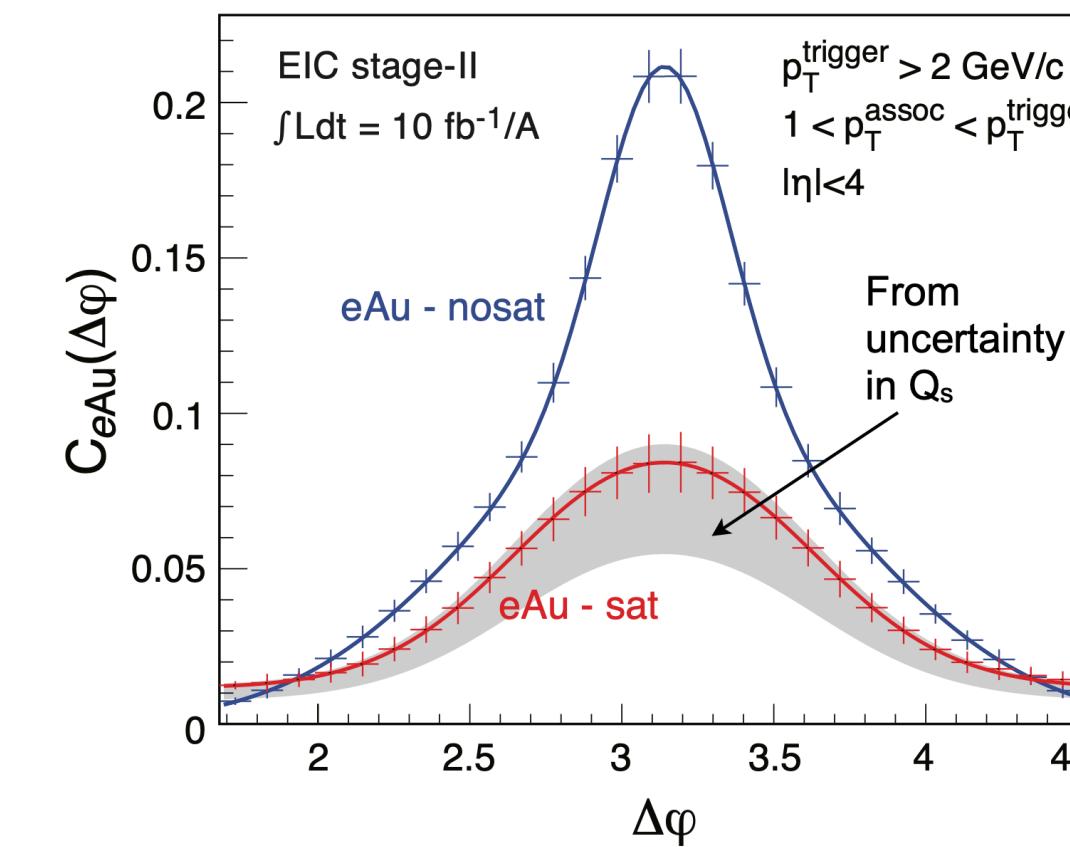
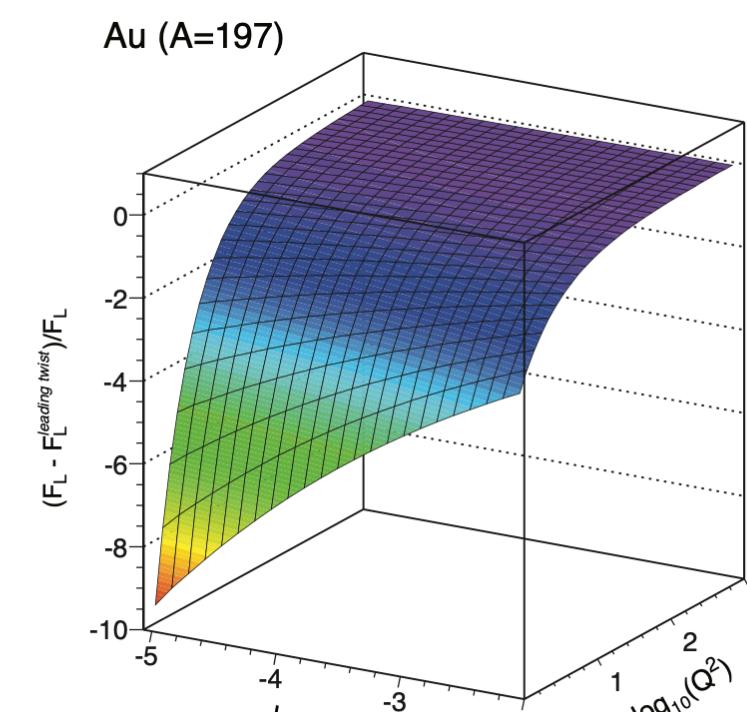
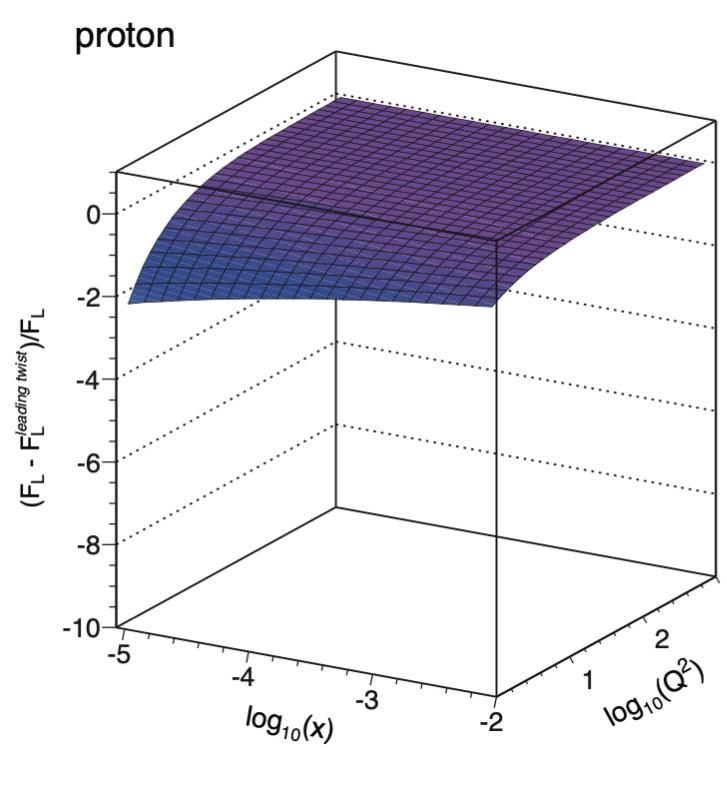
# Saturation

Using heavier ions helps with accessing the saturated regime



# Observables

- Inclusive: Structure functions
- Semi-inclusive: dihadron, dijet correlations
- Diffractive processes: e.g. ratio of diffractive and total cross-section, vector meson production, ...

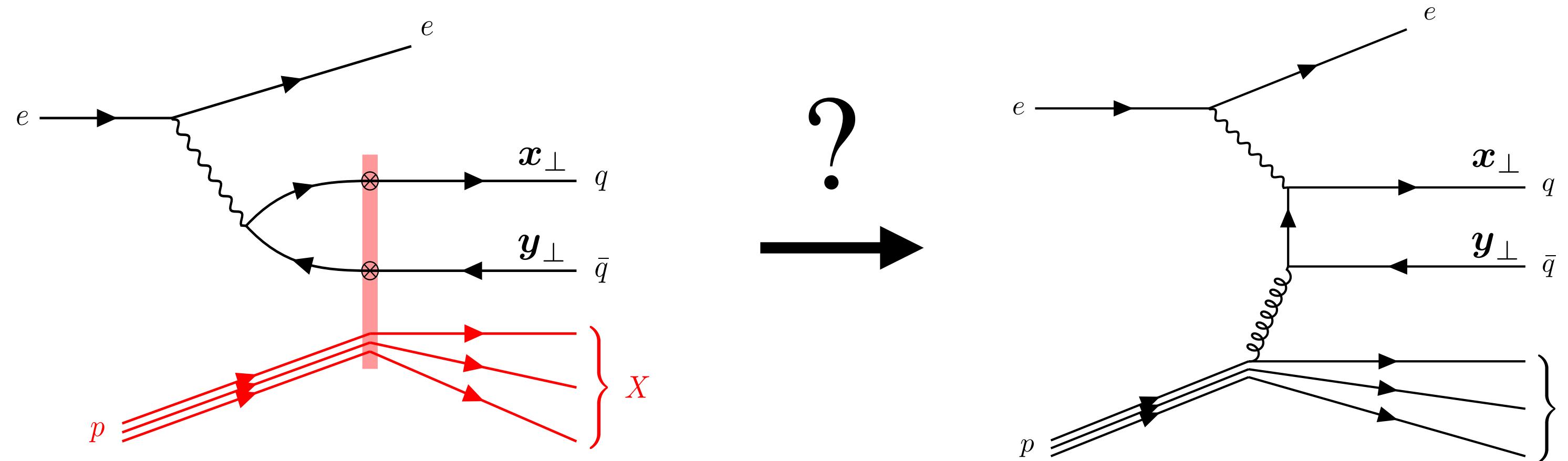


for the most recent review: [A. Morreale, F. Salazar, Universe 7 \(2021\) 8, 312 • e-Print: 2108.08254](#)

# **Update on theory developments**

# Matching TMD and CGC frameworks at small-x

CGC, improved TMD, and TMD frameworks



Mäntysaari, Mueller, Salazar, Schenke. [1912.05586](#)

Boussarie, Mäntysaari, Salazar, Schenke. [2106.11301](#)

$$d\sigma_{\text{CGC}} = \underbrace{d\sigma_{\text{TMD}} + \mathcal{O}\left(\frac{k_\perp}{Q_\perp}\right)}_{d\sigma_{\text{ITMD}}} + \mathcal{O}\left(\frac{Q_s}{Q_\perp}\right)$$

TMD valid  $k_\perp, Q_s \ll Q_\perp$

back-to-back hadrons/jets  
and transverse momenta larger than sat scale

see also: Dominguez, Marquet, Xiao, Yuan. [1101.0715](#),  
Altinoluk, Boussarie. [1902.07930](#), Boussarie, Mehtar-Tani. [2001.06449](#)

$$\begin{array}{c} \mathbf{p}_{1,\perp} \quad 2\mathbf{P}_\perp \quad \mathbf{k}_\perp \\ \swarrow \quad \searrow \quad \uparrow \\ \mathbf{p}_{2,\perp} \end{array} \quad Q_\perp \sim P_\perp, Q$$

Improved TMD valid  $Q_s \ll Q_\perp$

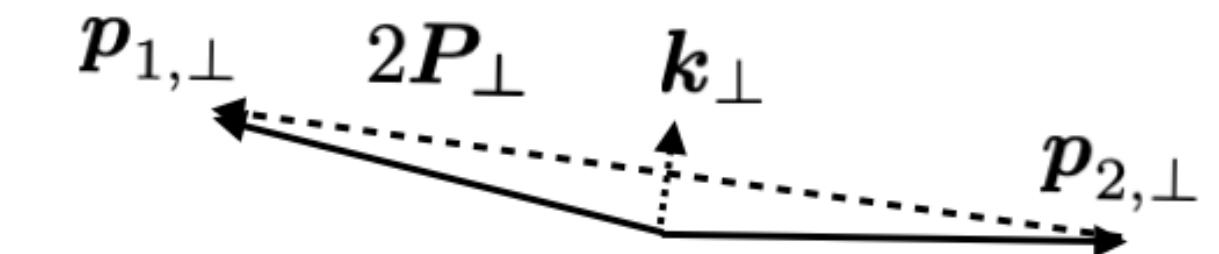
transverse momenta larger than saturation scale

No need for back-to-back!

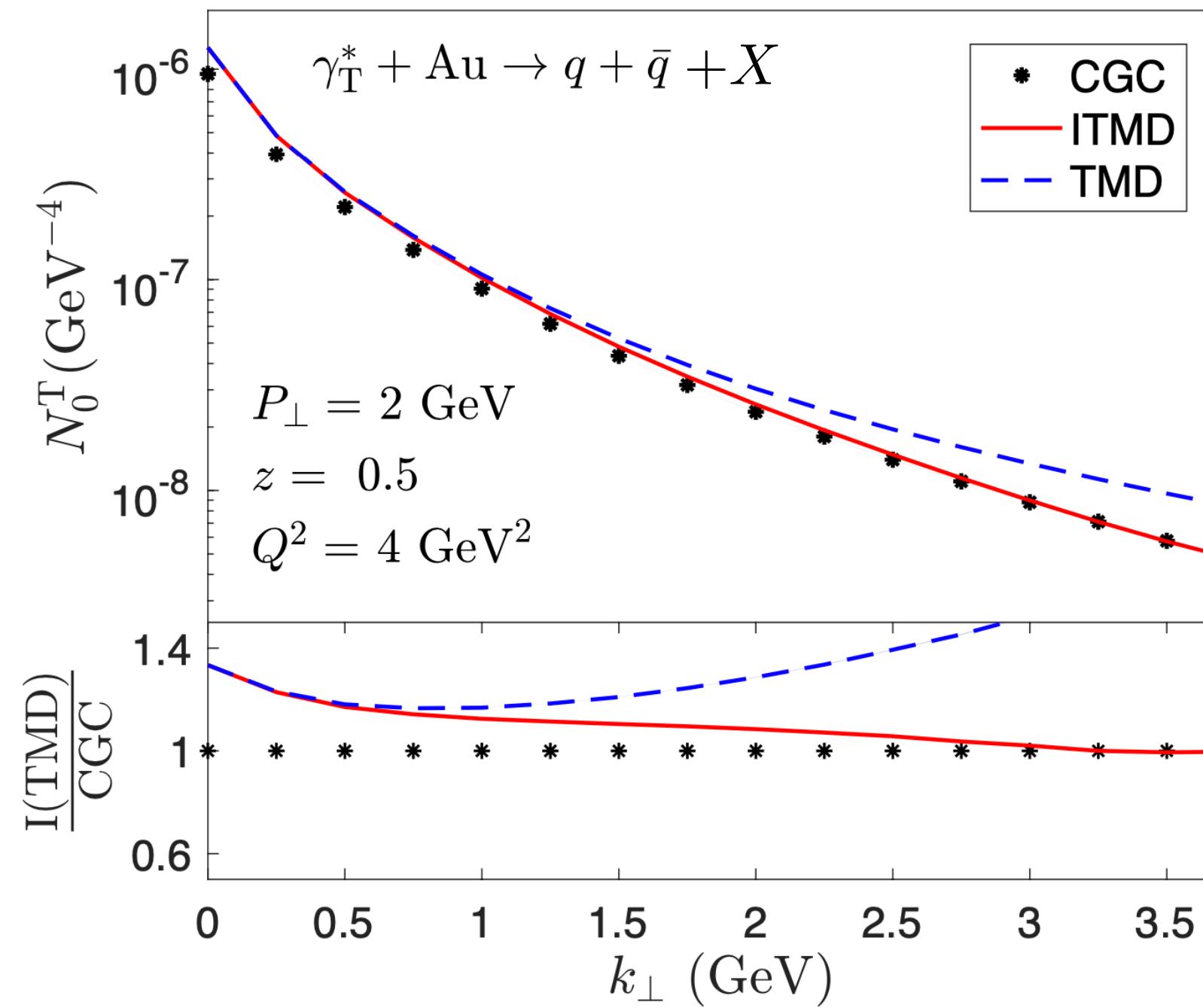
# Matching TMD and CGC frameworks at small-x

Kinematic and genuine saturation effects at the EIC

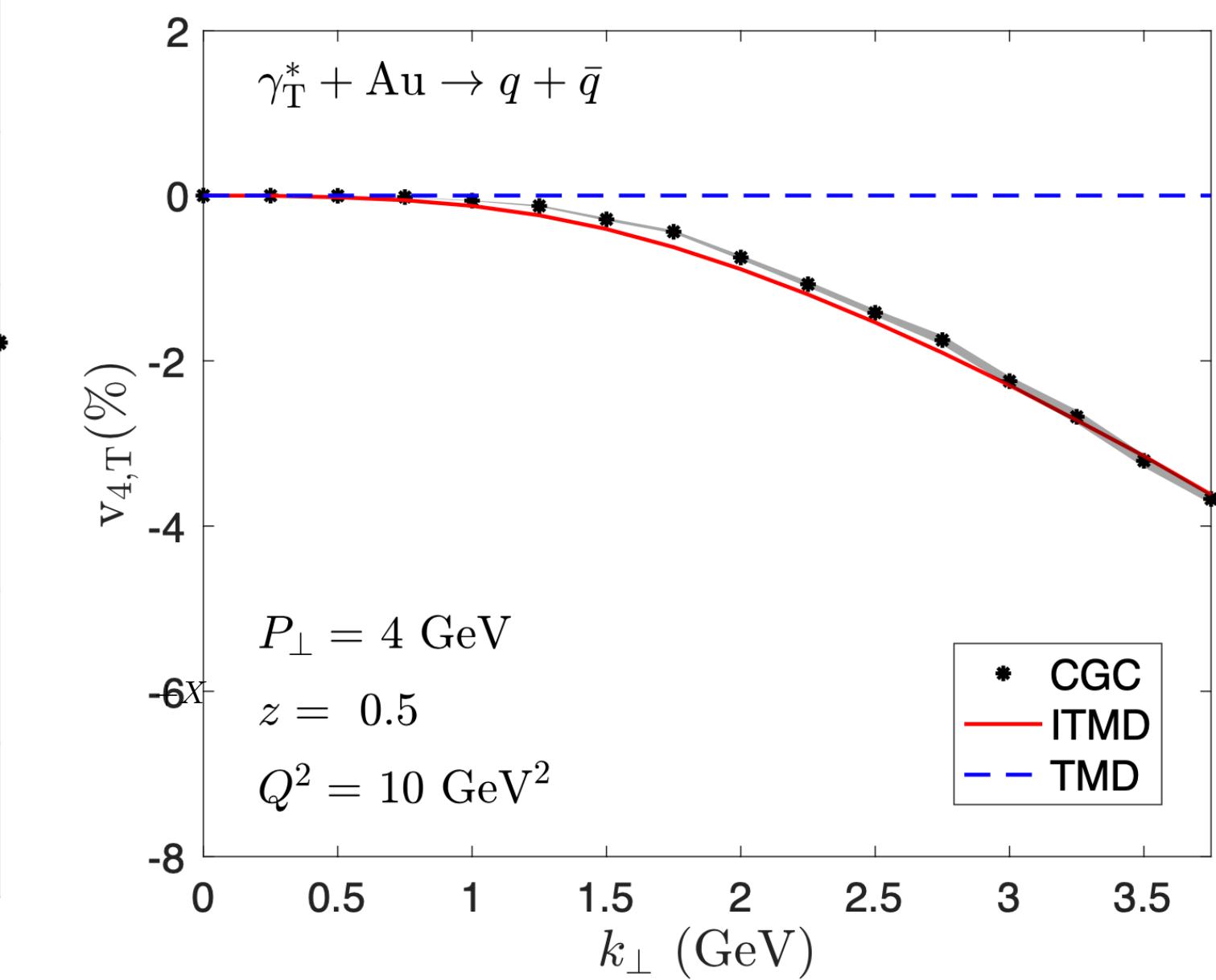
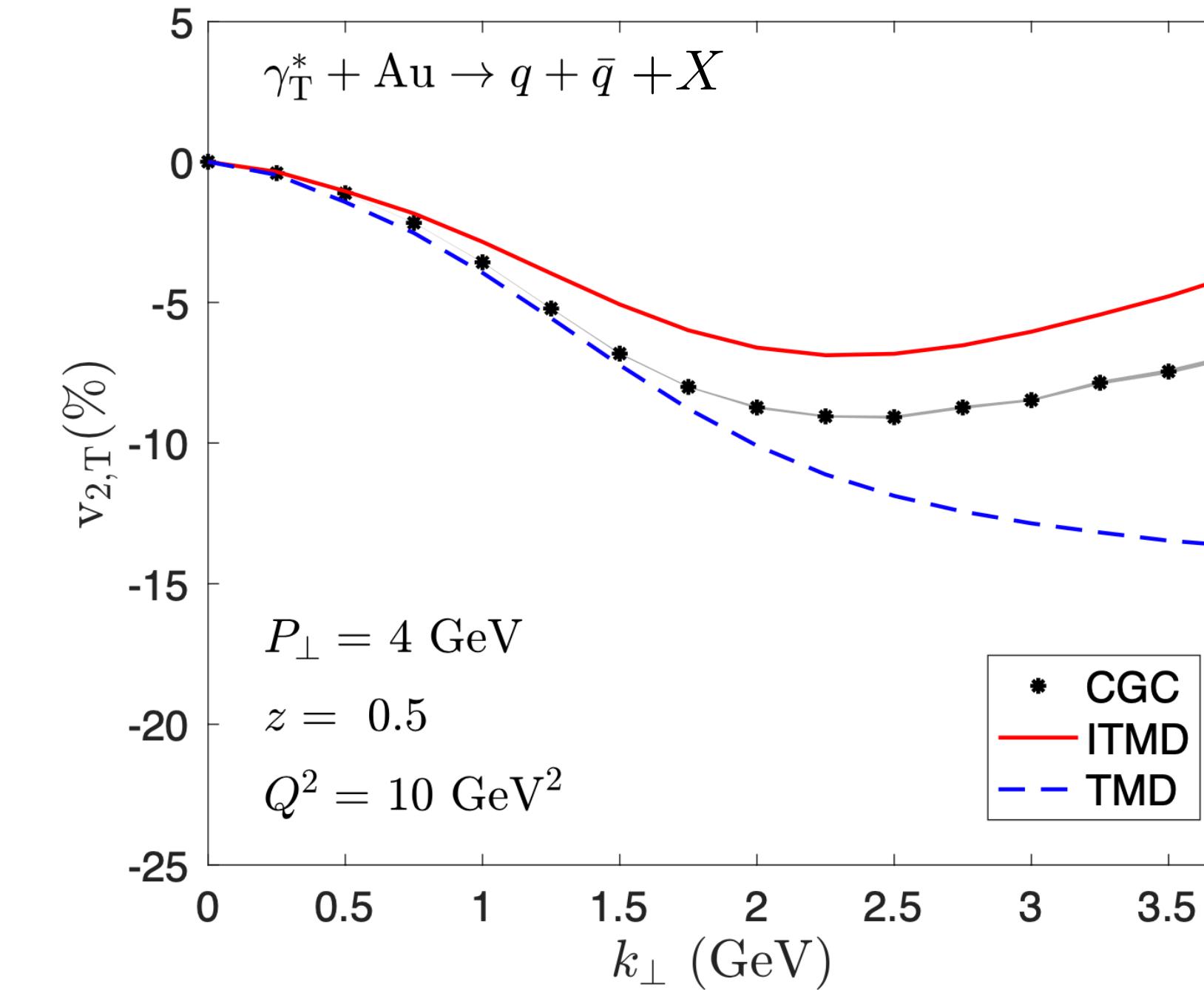
Boussarie, Mäntysaari, Salazar, Schenke. [2106.11301](#)



Differential yield



Momentum imbalance azimuthal anisotropies



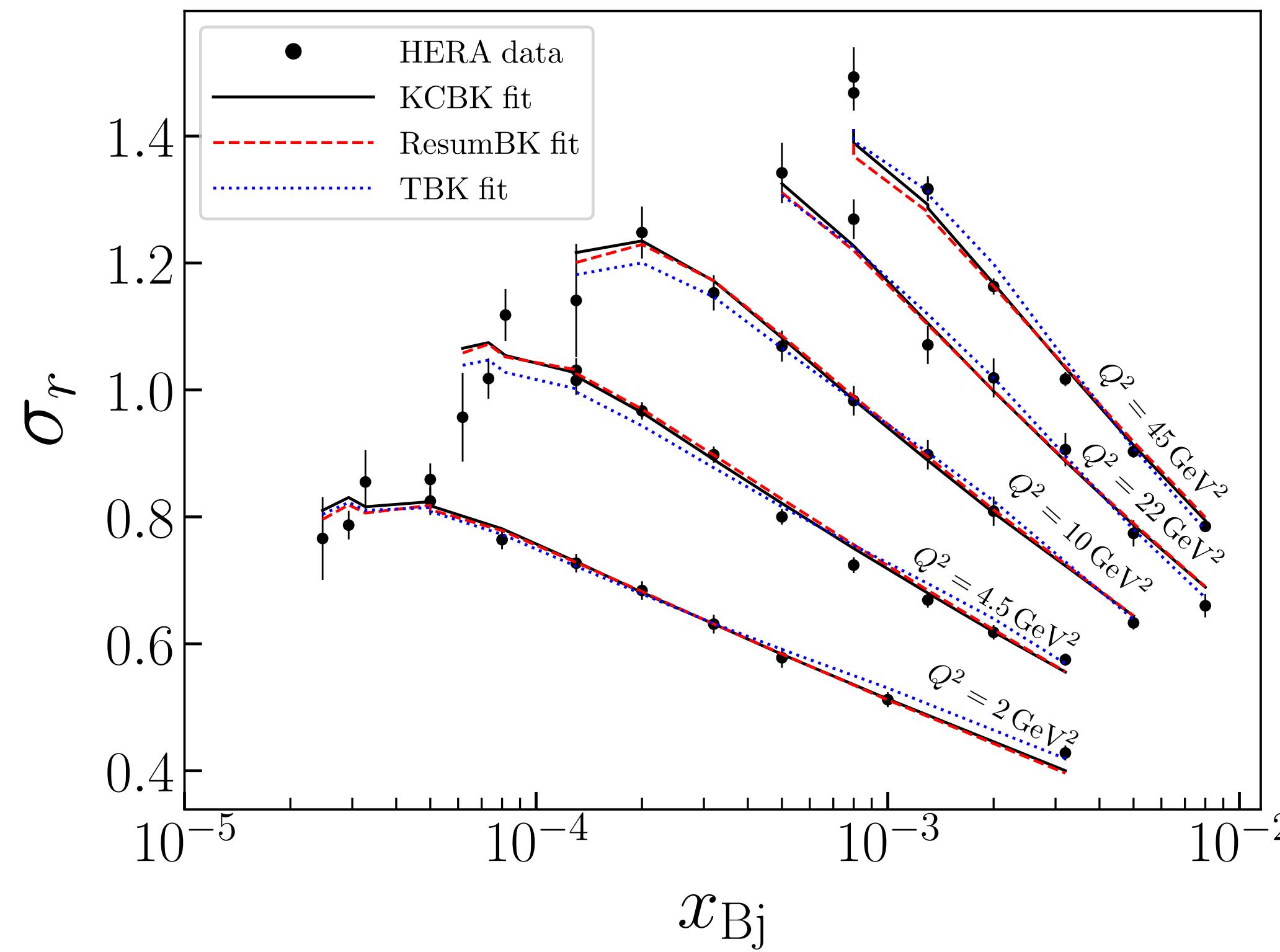
CGC shows further suppression relative to  
(I)TMD in back-to-back limit

Anisotropies modified in ITMD and CGC

# Update on next-to-leading order computations

## Recent advances of NLO computations

Reduced DIS cross-section fits with NLO BK + NLO impact factor\*

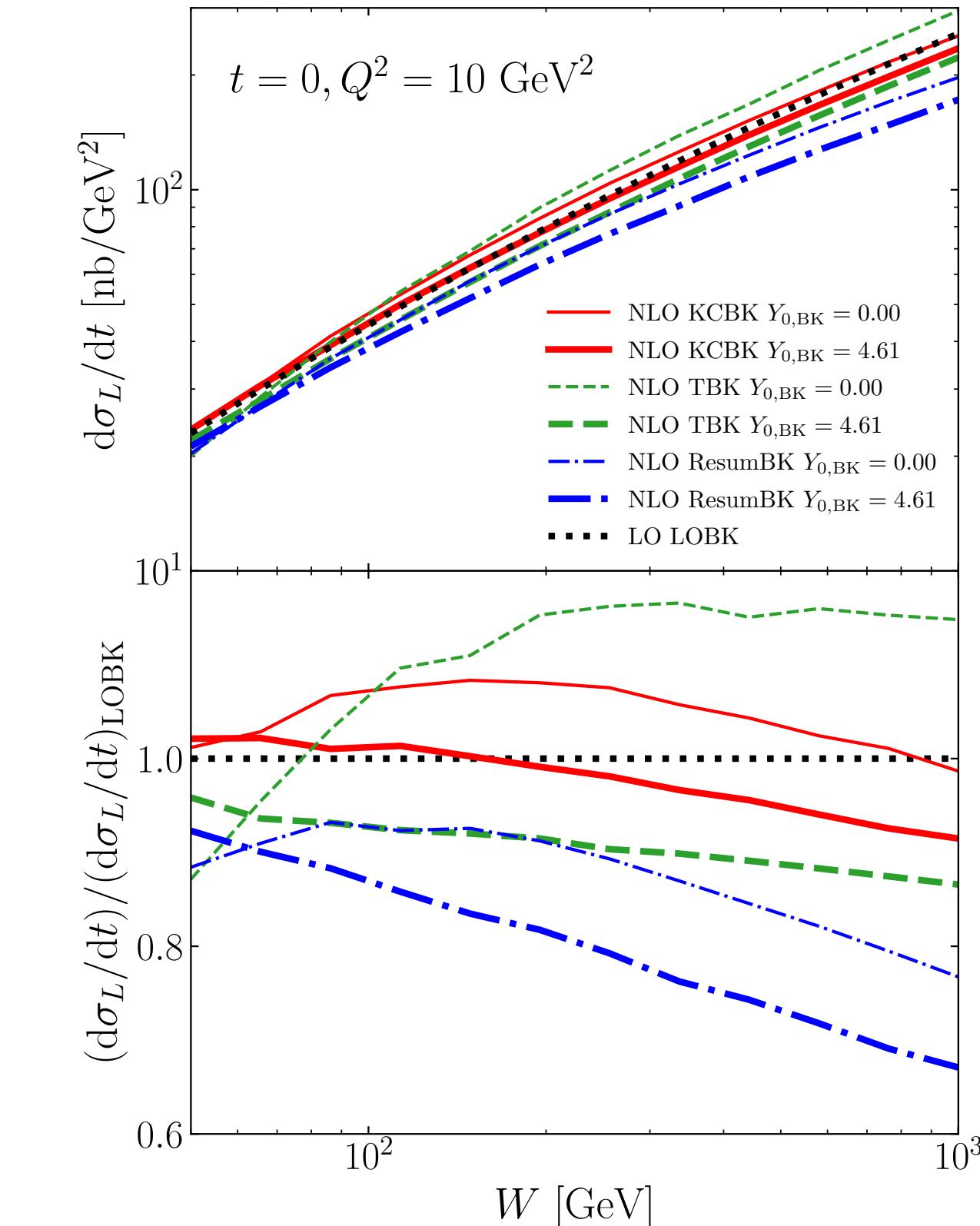


Should be extended to nuclear DIS  
for EIC predictions!

Beuf, Lappi, Hänninen, Mäntysaari. [2007.01645](#)

\* only light-quark contribution

$J/\Psi$  electron production (only L polarization) at NLO



Comparison with HERA data  
once T polarization is computed  
Mäntysaari, Penttala. [2104.02349](#)

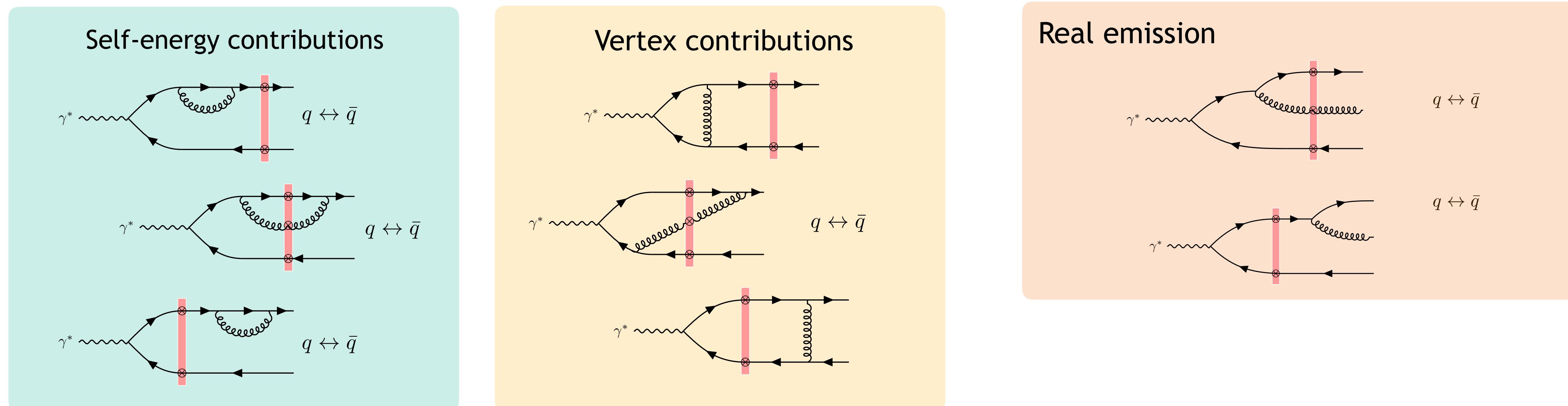
# Update on next-to-leading order computations

## Dijet production at NLO

Caucal, Salazar, Venugopalan. 2108.06347

see also Roy, Venugopalan. [1911.04530](#) for photon+dijet

### Computation of real and virtual contributions to inclusive dijet production



- *Cancellation of divergences: UV, soft and collinear*
- *Slow gluon divergence absorbed in redefinition of sources via Leading Log JIMWLK evolution*
- *Numerically tractable expressions for impact factor*

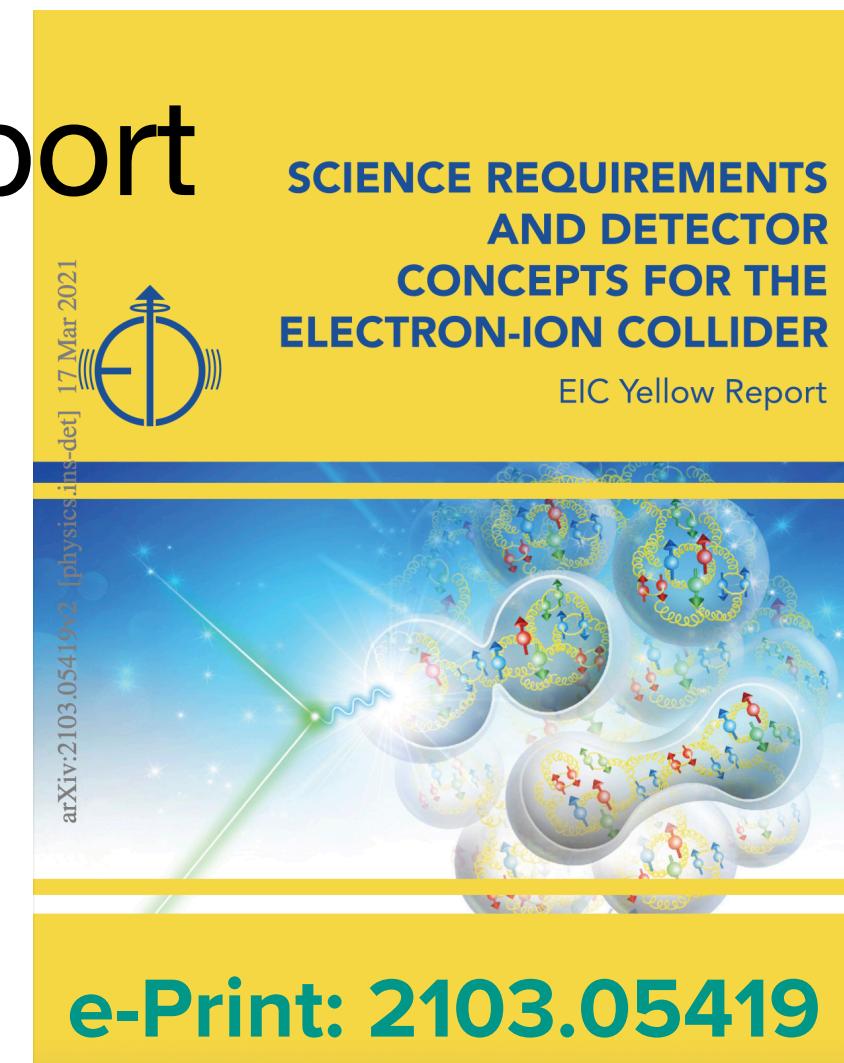
Numerical evaluation to be done.

# More contributions to the document

- Inclusive diffraction, exclusive vector meson production and DVCS at the EIC  
**Stasto, Yuan, Hentschinski**  
(e.g. discussion longitudinal diffractive structure function, access to elliptic gluon Wigner distribution, i.e. detailed structure of gluon distribution)
- Quark and Gluon quasi-PDFs at low x  
**Chirilli**  
(discussing the need and methods to improve theory calculations to keep up with expected precision at the EIC)
- Gluon saturation and spin diffusion at small x:  
Axion-like dynamics and topological transitions  
**Venugopalan**  
(effect of saturation scale on process of spin diffusion)
- Helicity evolution at small x: Preparing for EIC  
**Kovchegov**  
(addressing the small x part of the proton spin puzzle)

# Summary

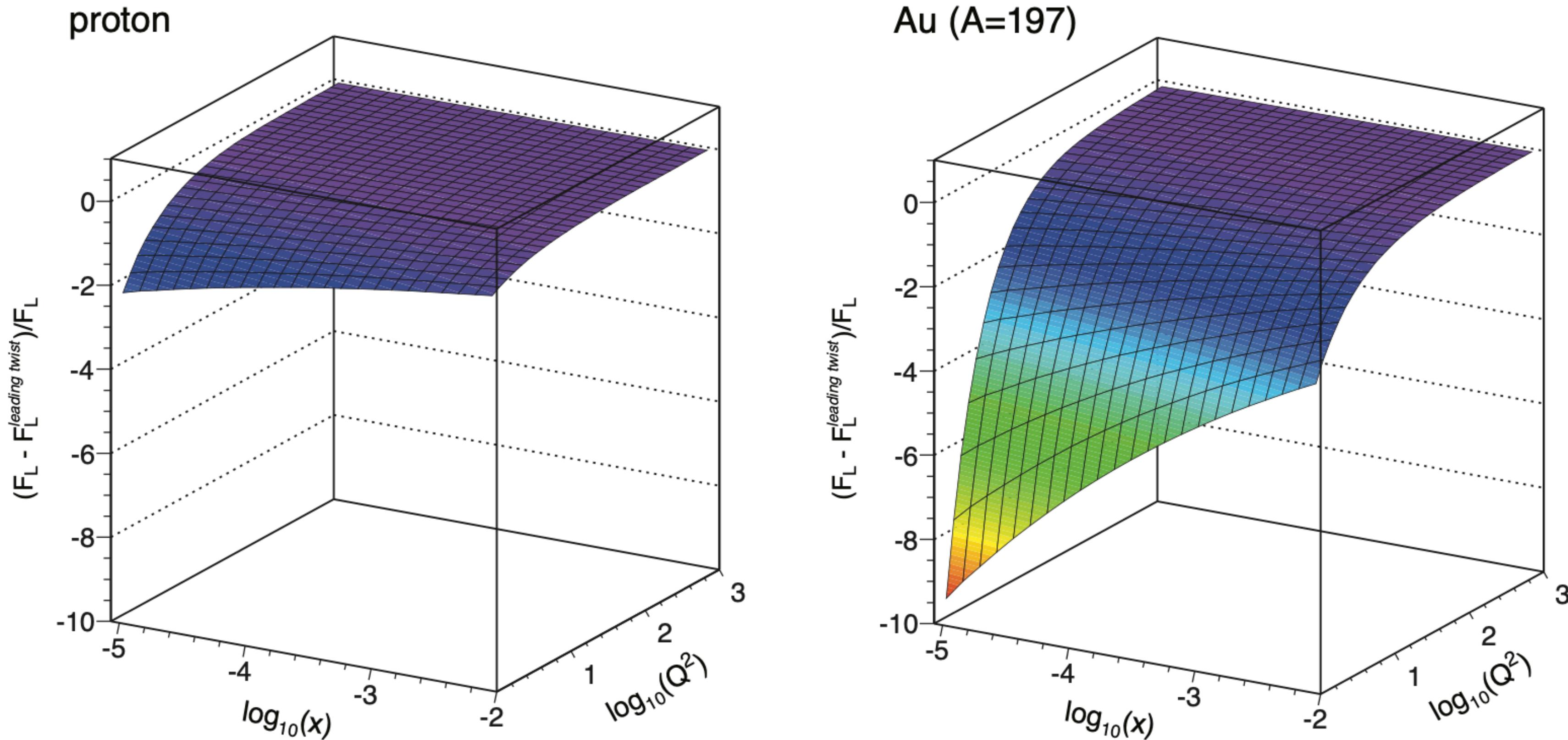
- The EIC is expected to start operation in 2030 and the experimental identification and study of gluon saturation is one of its major science goals
- Gluon saturation becomes increasingly important also for particle production in hadronic collisions as the collision energy increases
- A series of observables has been identified and predictions are improving
- Theory is advancing significantly, moving on to NLO calculations
- Detailed studies for detector requirements in the EIC Yellow Report



# **Backup - slides from previous workshop**

# Saturation effects on structure functions

J. Bartels, K. Golec-Biernat, and L. Motyka, Phys. Rev. D81, 054017 (2010)

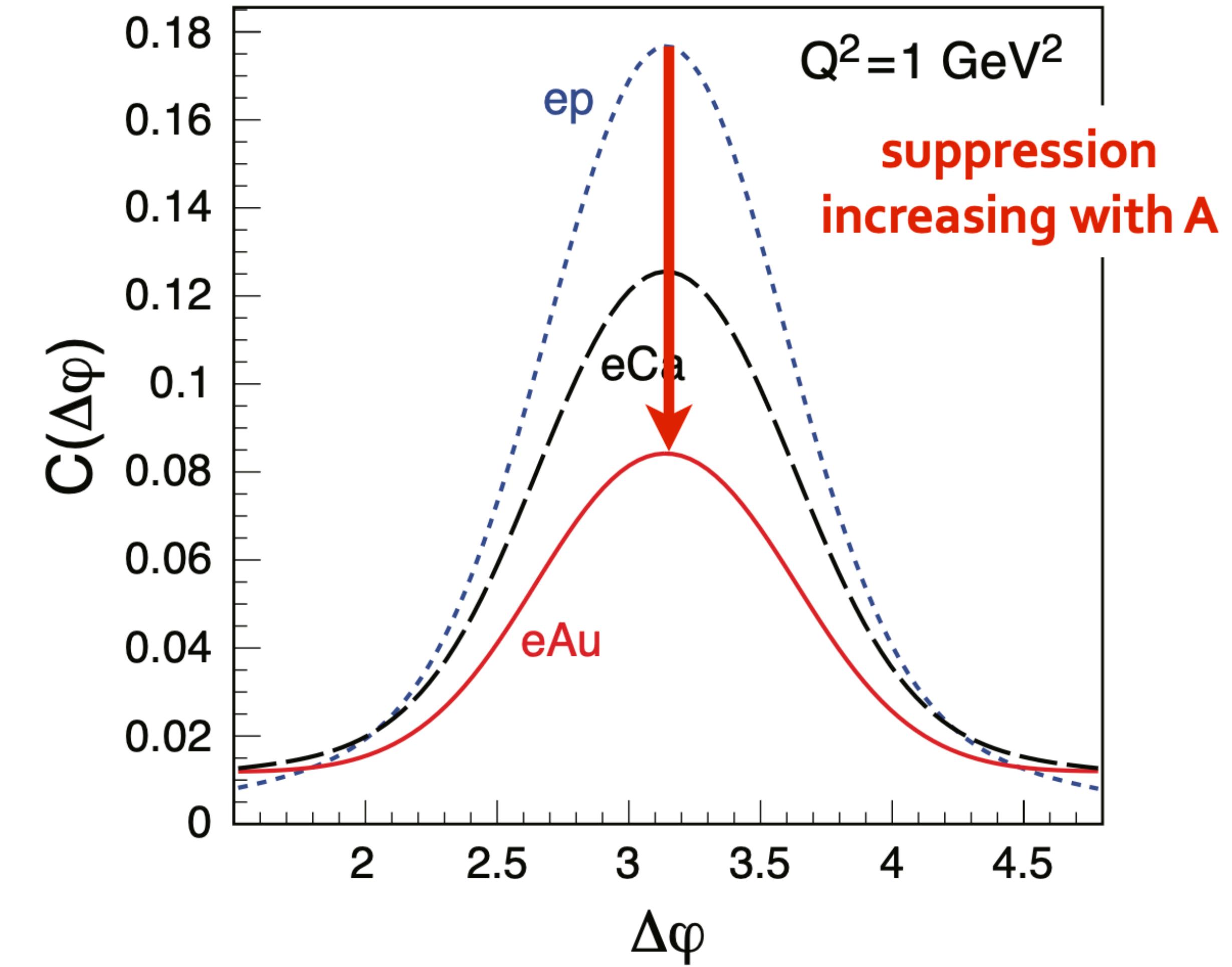
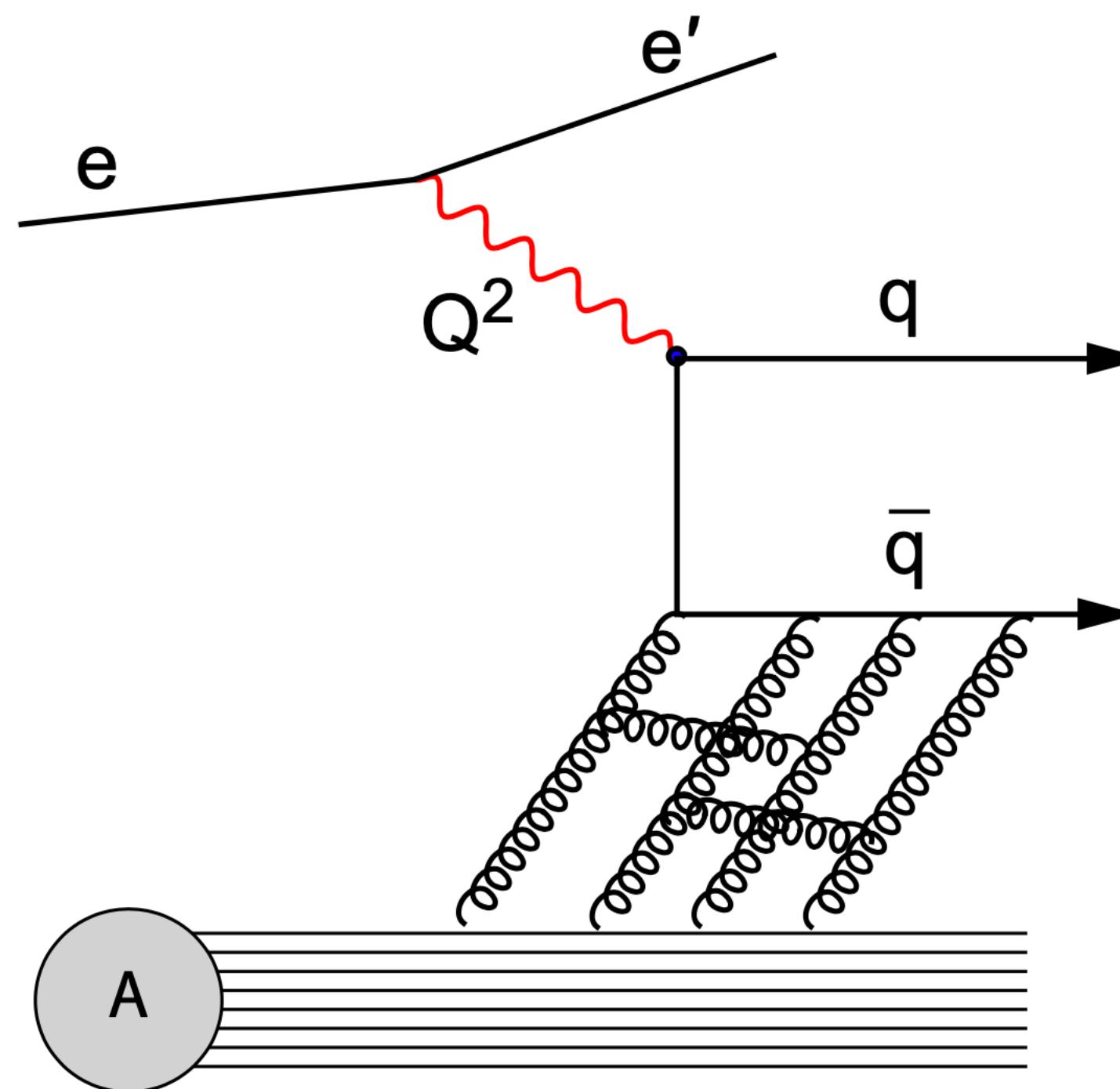
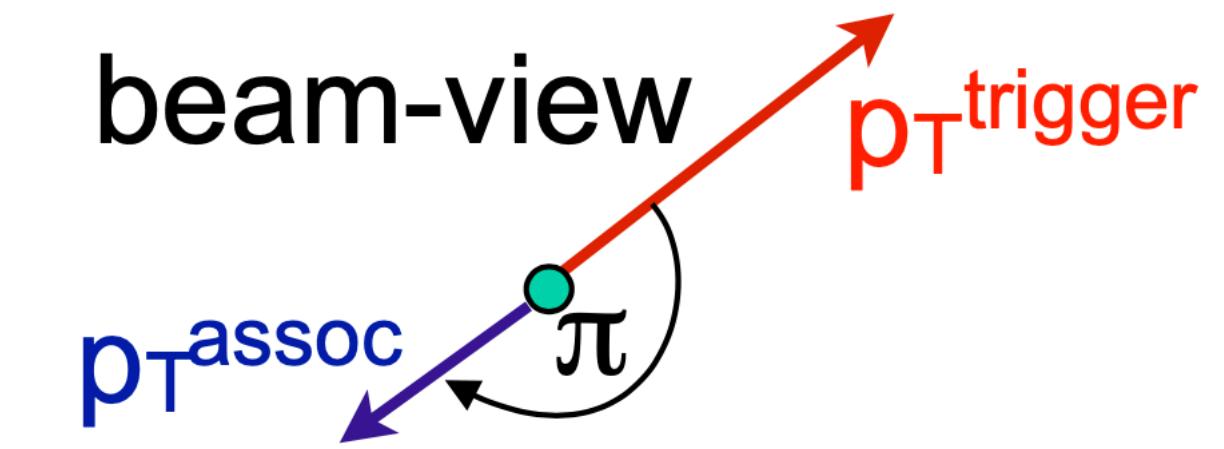


The multiple re-scatterings and gluon mergers contribute at all orders in twists (terms in a  $1/Q^2$  expansion). Their effect increases with increasing  $A$  and decreases with increasing  $x$

# Semi-inclusive DIS

C. Marquet, B. -W. Xiao and F. Yuan, Phys. Lett. B 682 (2009) 207

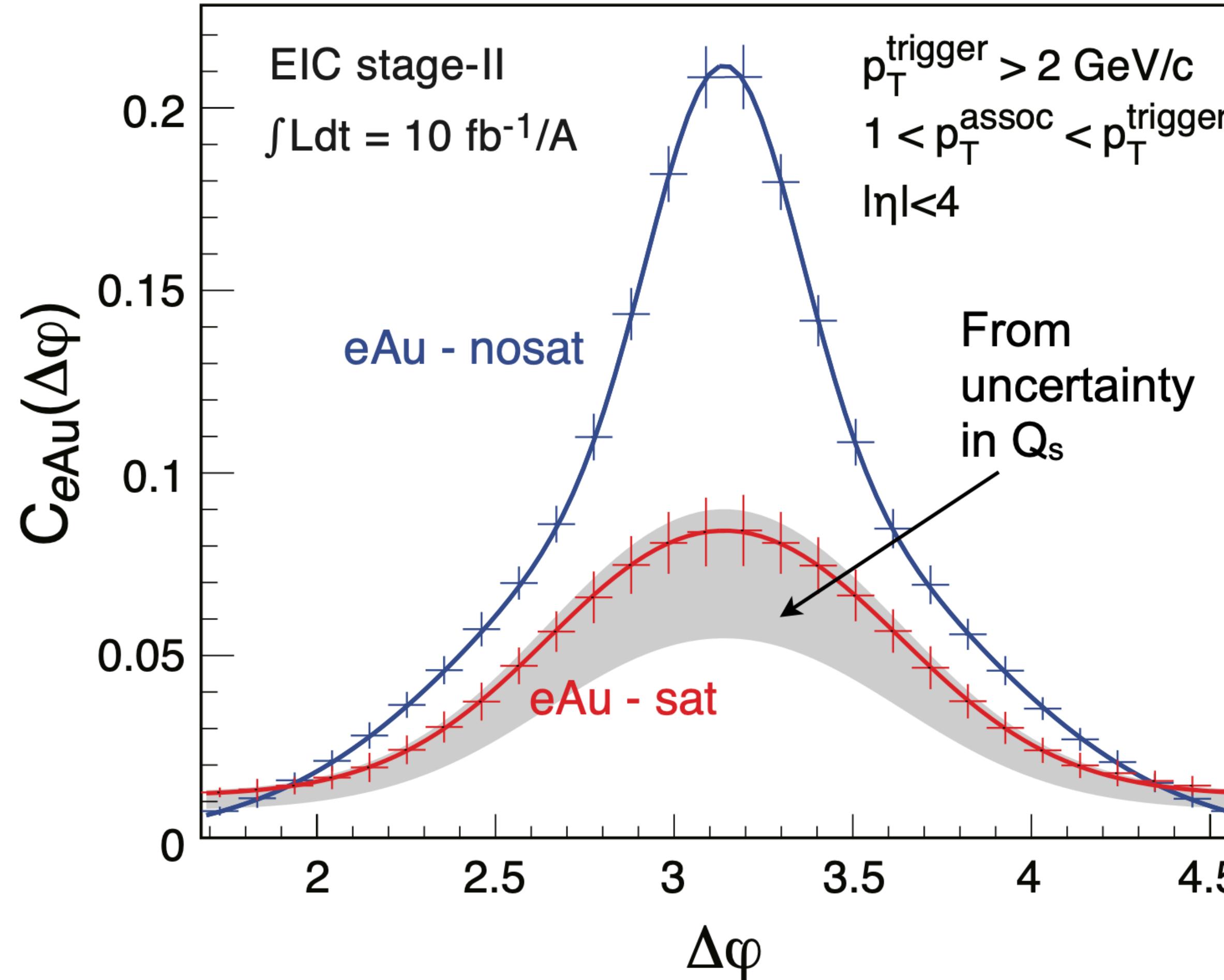
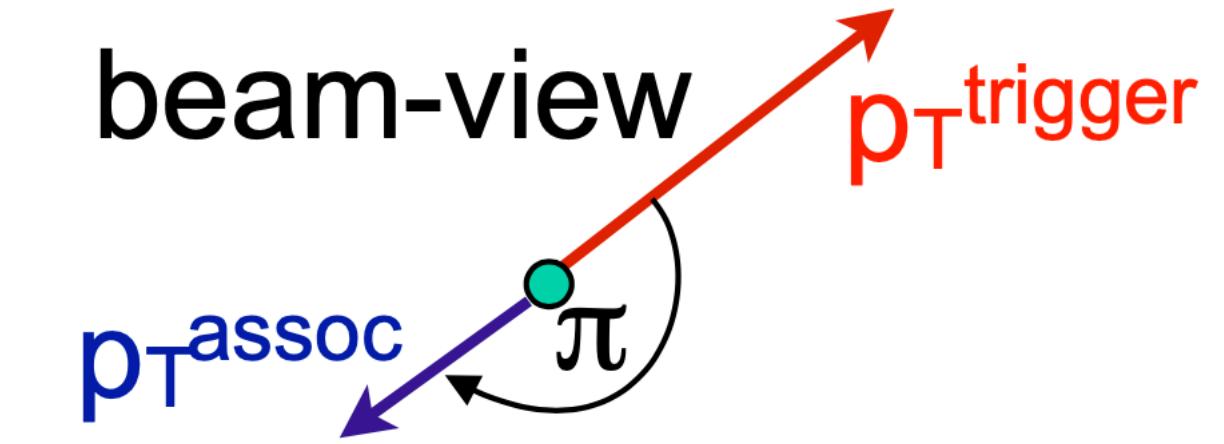
L. Zheng, E.C. Aschenauer, J.H. Lee, Bo-Wen Xiao, Phys. Rev. D 89, 074037 (2014)



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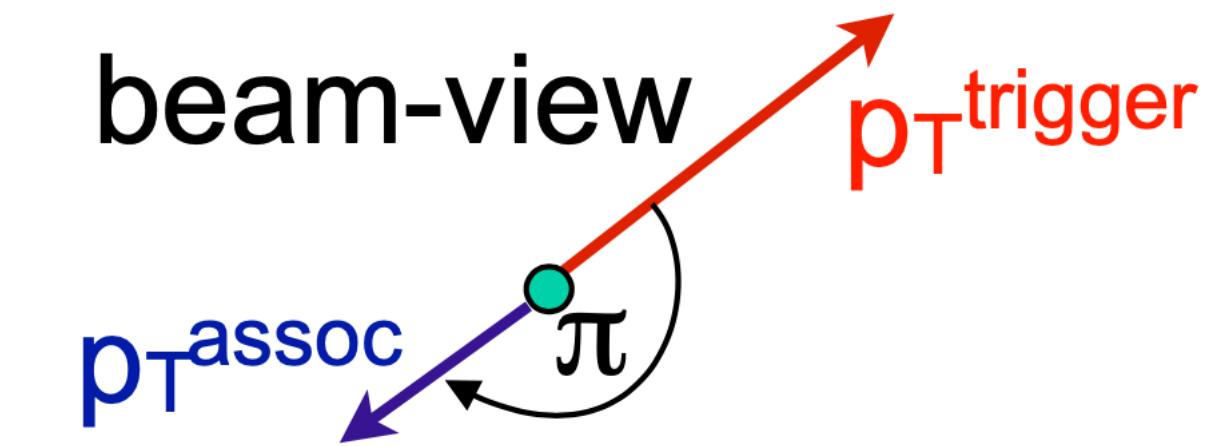
Clear key measurement

- Significant difference between sat and non-sat case
- Has equivalent to pA (e.g. RHIC forward measurements)
- Parton showers can modify predictions

# Semi-inclusive DIS

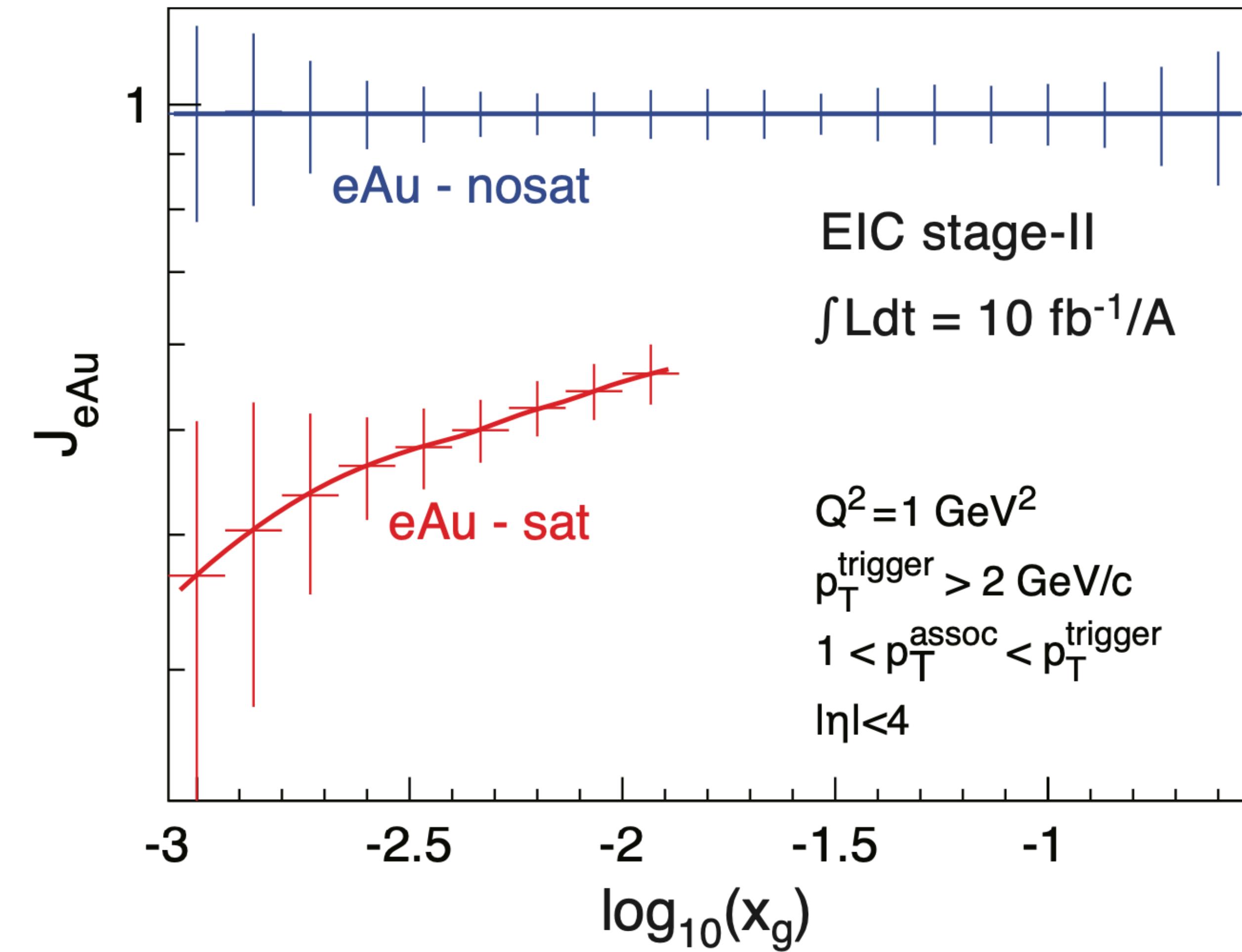
C. Marquet, B. -W. Xiao and F. Yuan, Phys. Lett. B 682 (2009) 207

L. Zheng, E.C. Aschenauer, J.H. Lee, Bo-Wen Xiao, Phys. Rev. D 89, 074037 (2014)

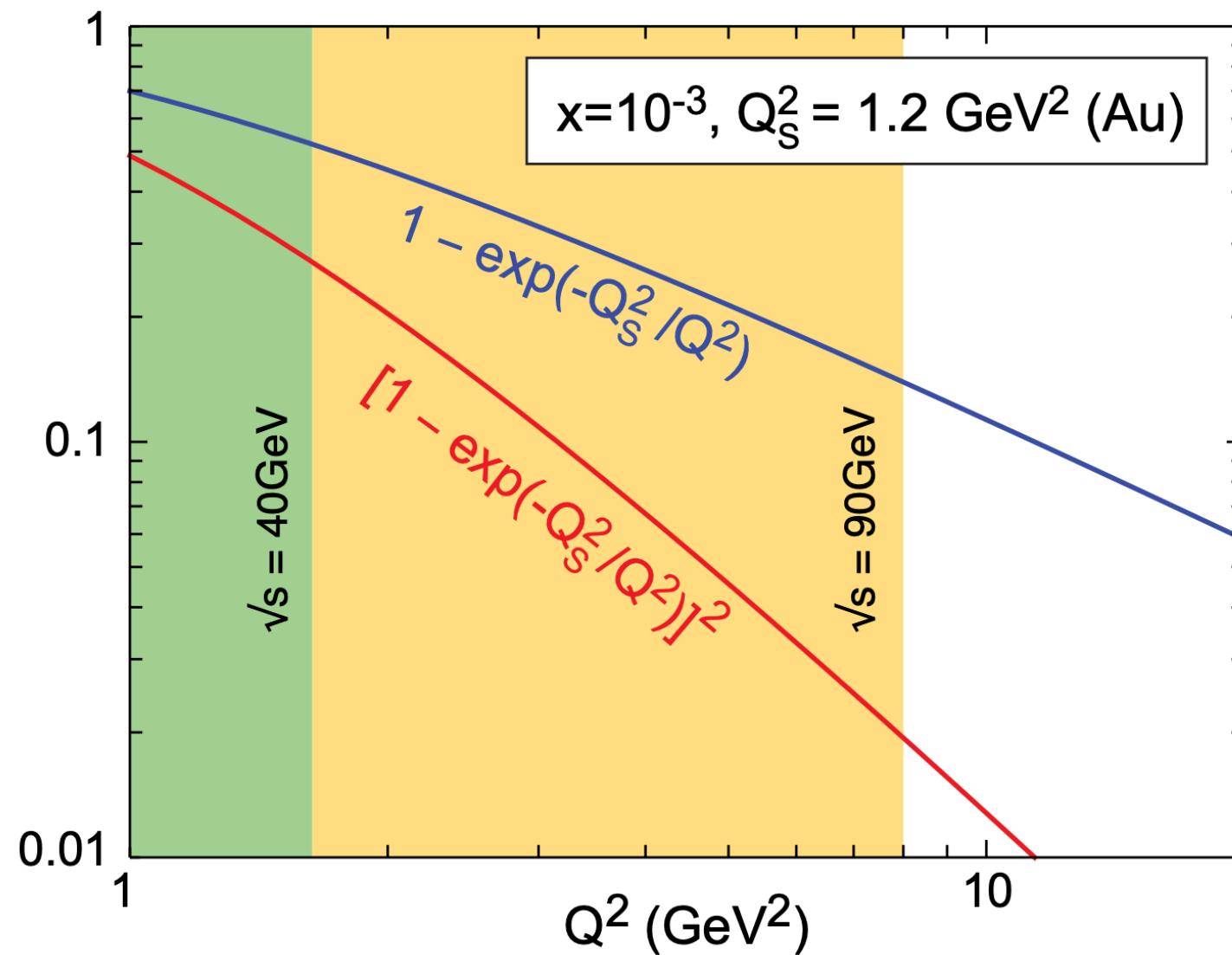


$$J_{eA} = \frac{1}{A^{1/3}} \frac{\sigma_{eA}^{\text{pair}} / \sigma_{eA}}{\sigma_{ep}^{\text{pair}} / \sigma_{ep}}$$

The absence of collective nuclear effects in the back-to-back pair production cross section,  $\sigma_{eA}^{\text{pair}}$ , corresponds to  $J_{eA} = 1$



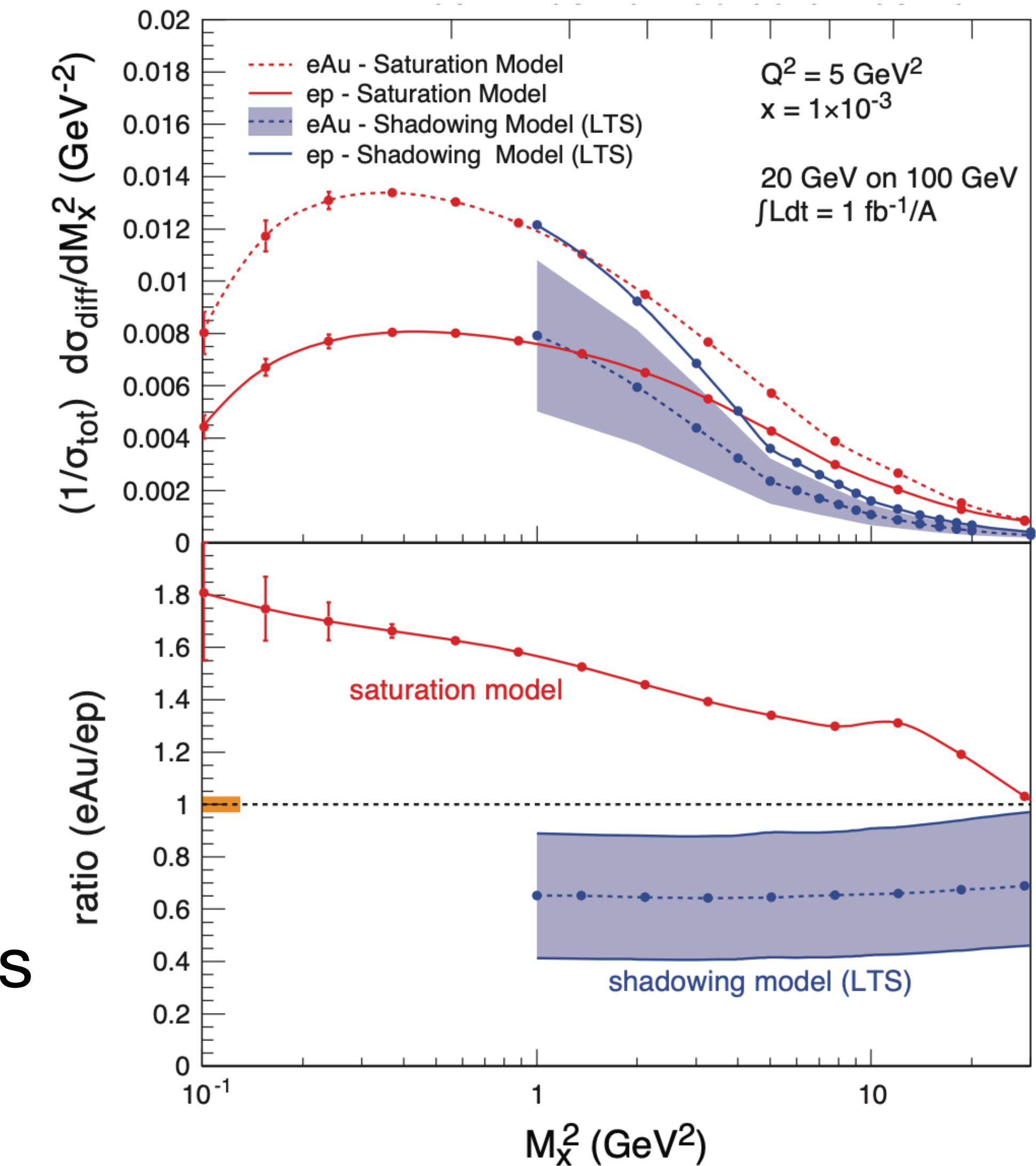
# Diffractive processes



Sensitivity of the **inclusive DIS** and **diffractive** cross sections on the dipole scattering amplitude

Ratio of diffractive and total cross-section in ep and eAu collisions →

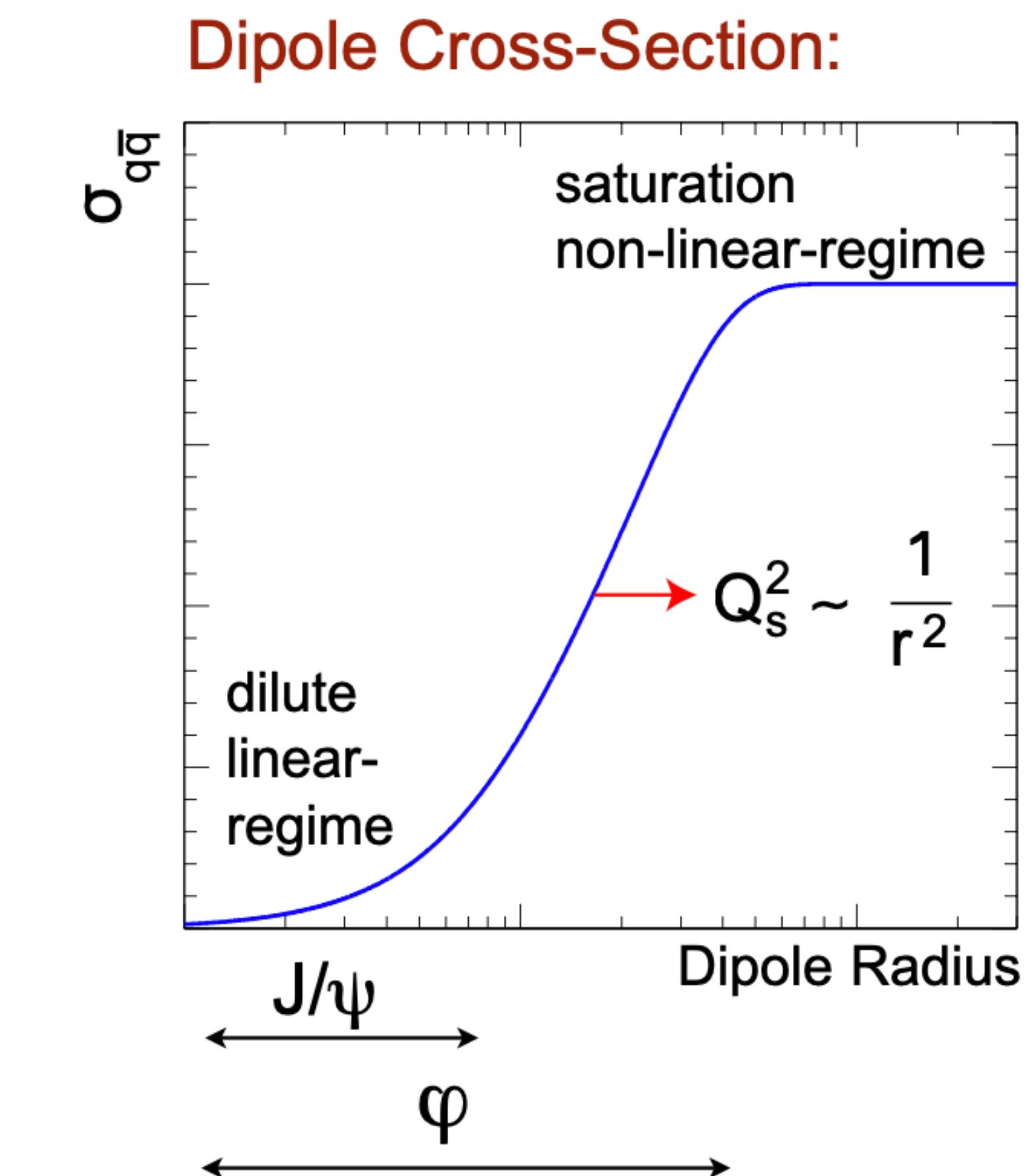
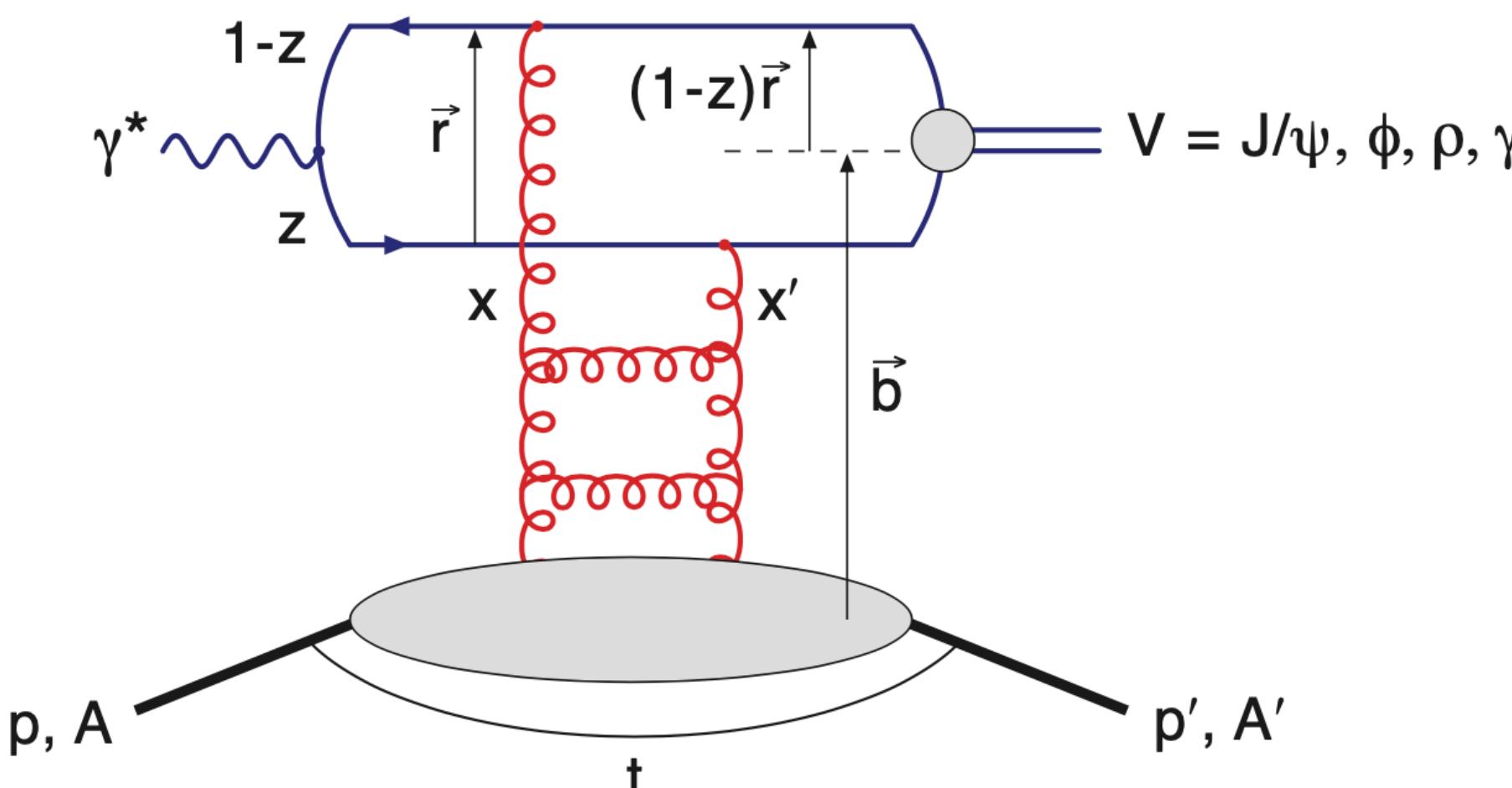
Clear difference between saturation models and leading twist shadowing (LTS)



# Diffractive vector meson production

Exclusive vector meson production:  
Allows measurement of momentum transfer  $t$

$$\begin{aligned} t &= (\mathbf{p}_A - \mathbf{p}_{A'})^2 = (\mathbf{p}_{VM} + \mathbf{p}_{e'} - \mathbf{p}_e)^2 \\ &\approx (p_T(e') + p_T(VM))^2 \end{aligned}$$



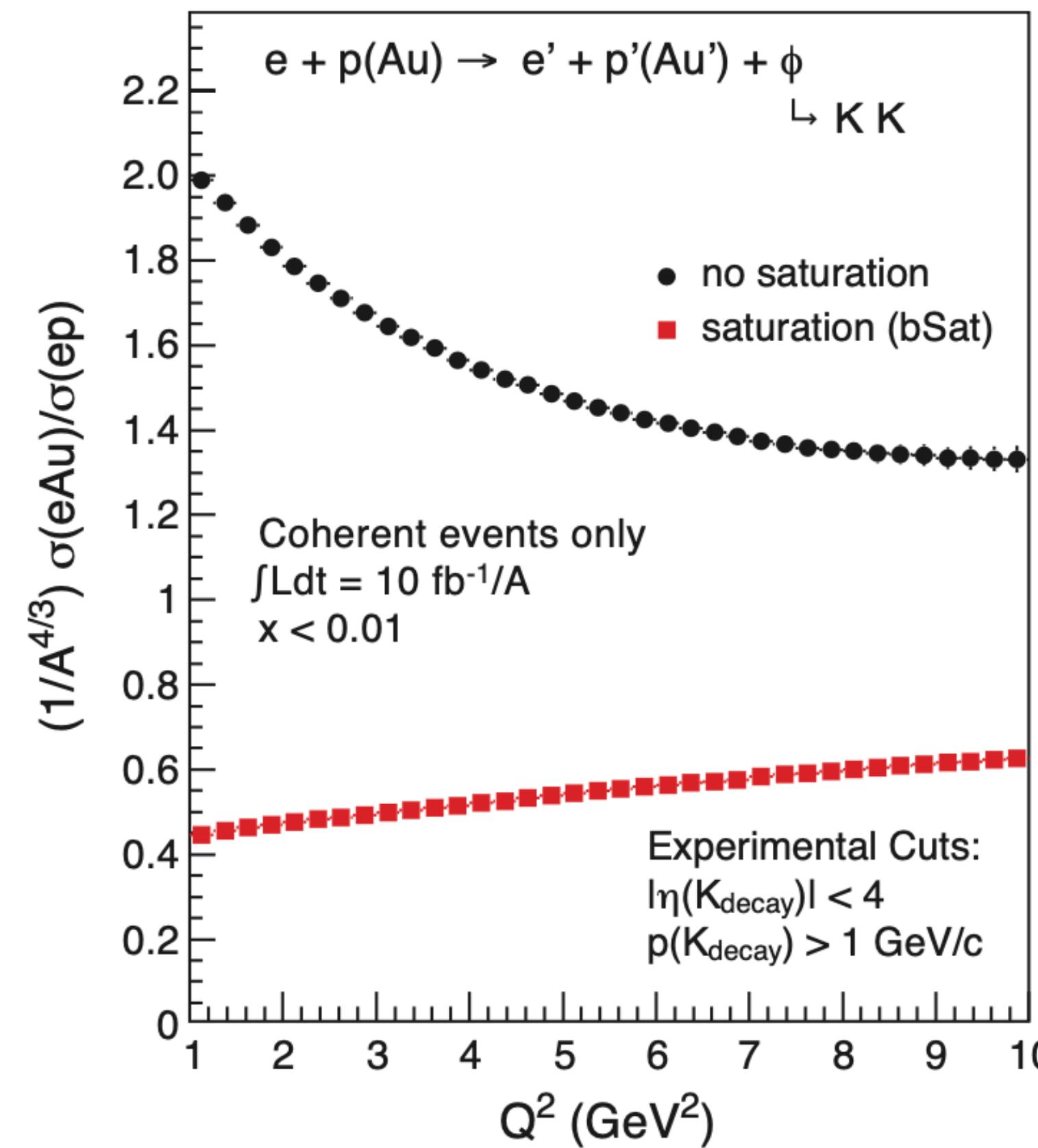
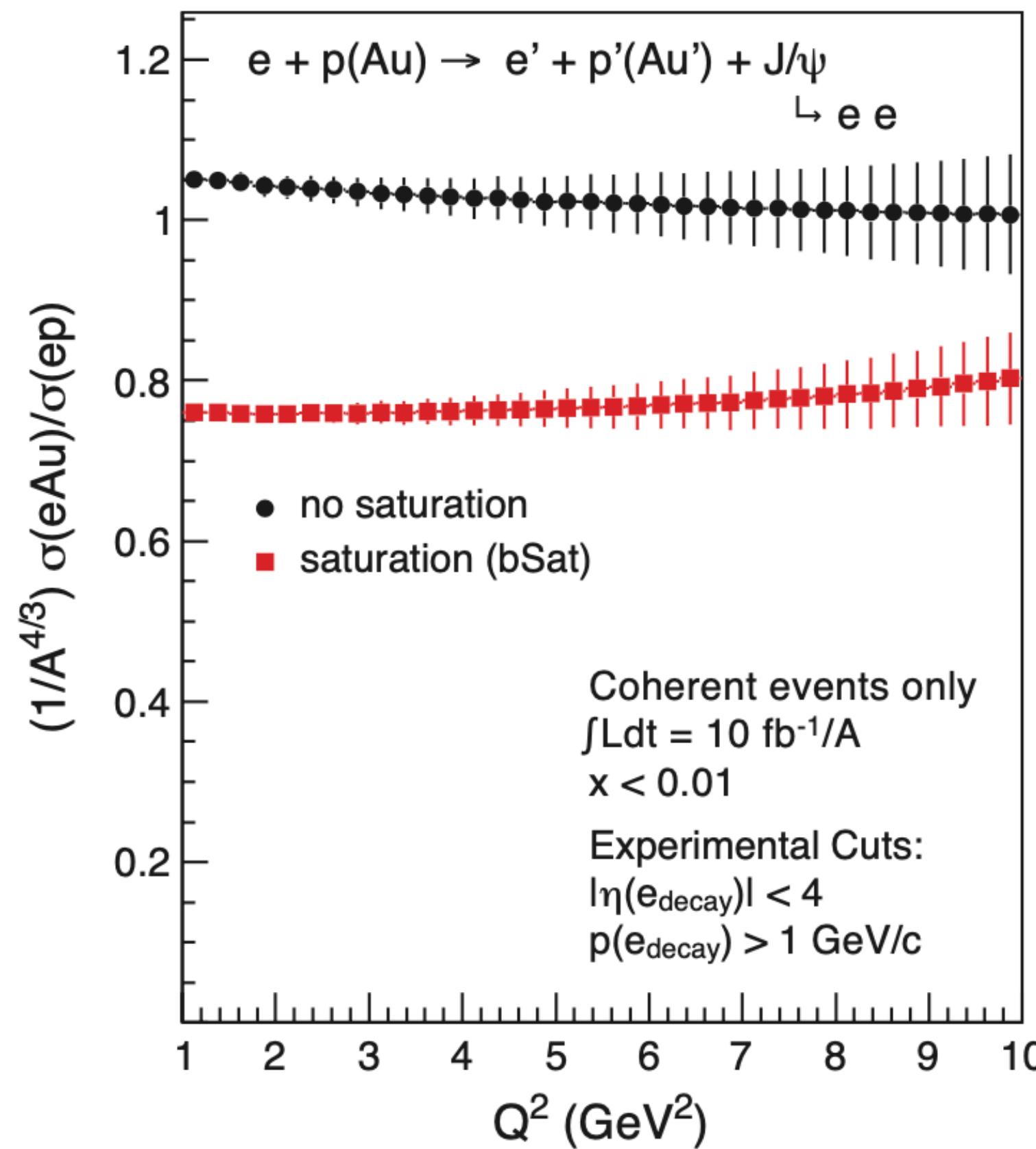
Large dipole sizes: More sensitive to saturation

Large vector meson mass and large  $Q^2$  cut off large dipole sizes

# Diffractive vector meson production

T. Toll, T. Ullrich, Phys.Rev.C 87 (2013) 2, 024913

A. Accardi et al., EIC White Paper, Eur.Phys.J.A 52 (2016) 9, 268

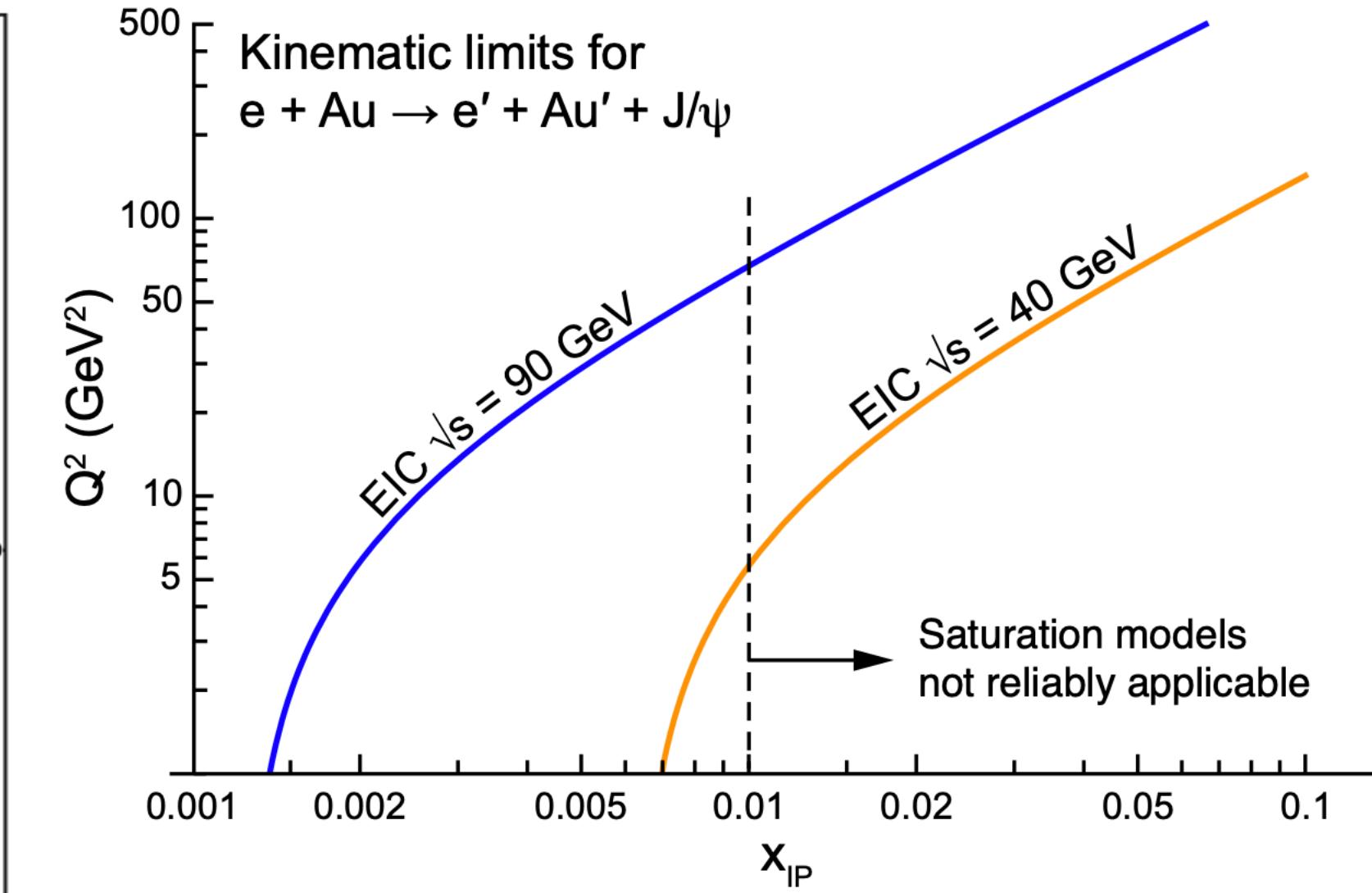
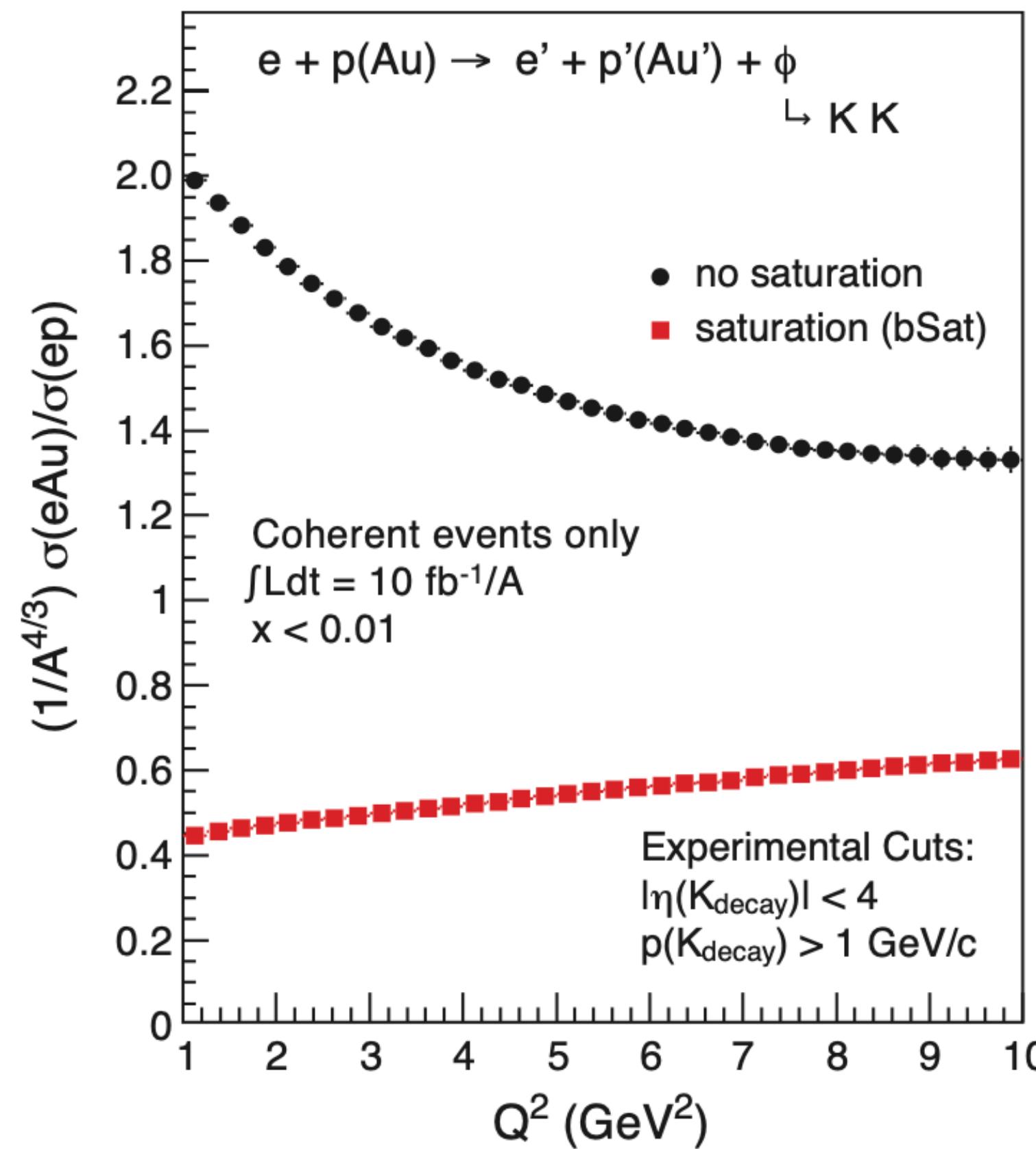
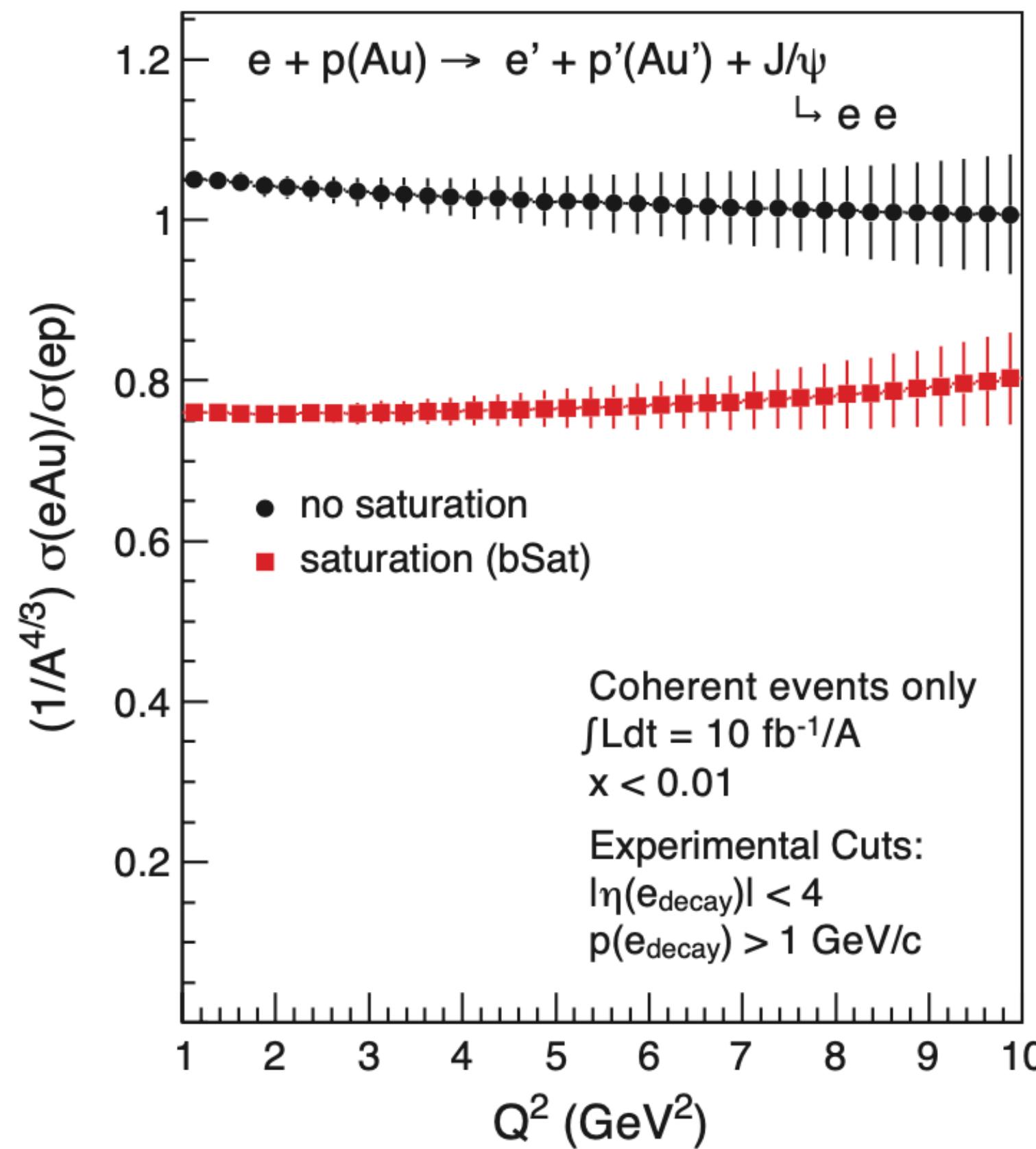


- Sartre event generator (bSat & bNonSat = linearized bSat)
- As expected: big difference for  $\phi$  less so for  $J/\psi$

# Diffractive vector meson production

T. Toll, T. Ullrich, Phys.Rev.C 87 (2013) 2, 024913

A. Accardi et al., EIC White Paper, Eur.Phys.J.A 52 (2016) 9, 268



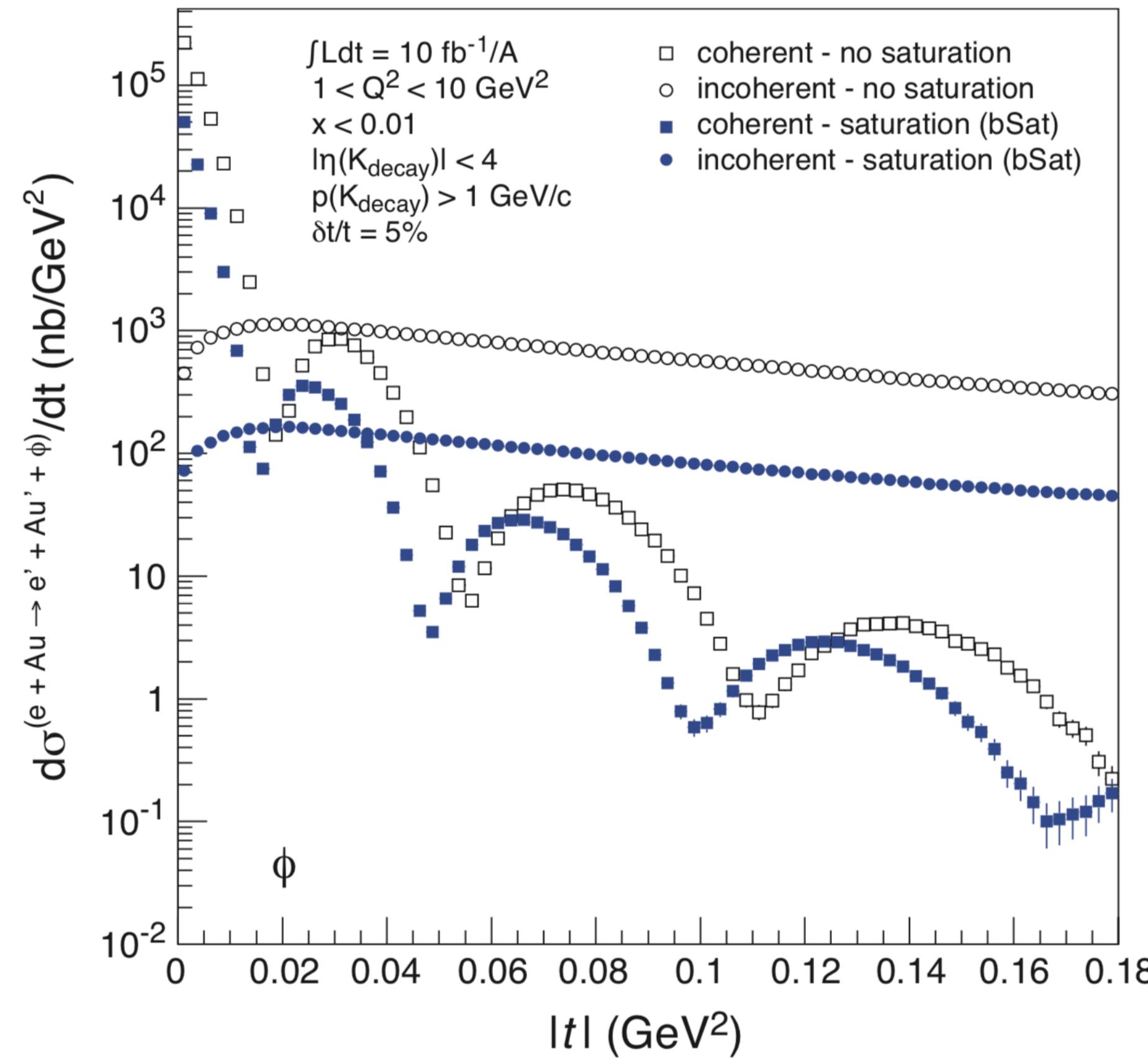
We want high energies to probe saturation

- Sartre event generator (bSat & bNonSat = linearized bSat)
- As expected: big difference for  $\phi$  less so for  $J/\psi$

# Diffractive vector meson production

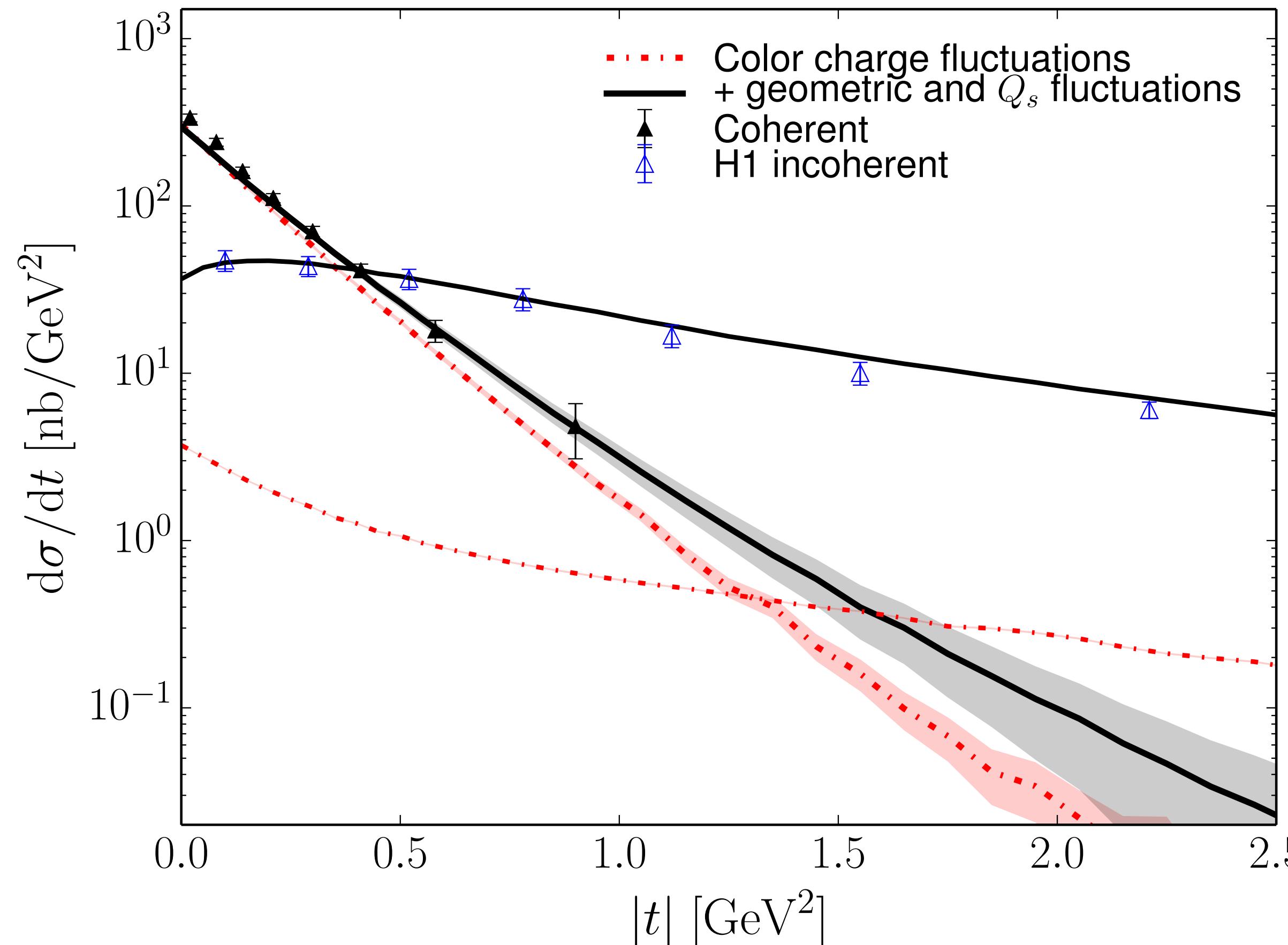
T. Toll, T. Ullrich, Phys.Rev.C 87 (2013) 2, 024913

A. Accardi et al., EIC White Paper, Eur.Phys.J.A 52 (2016) 9, 268



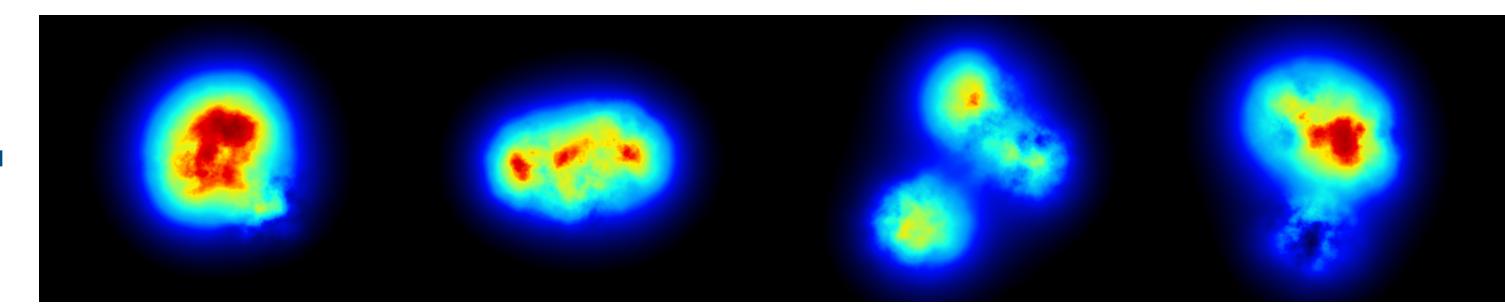
# Diffractive vector meson production

H. Mäntysaari, B. Schenke, Phys. Rev. Lett. 117 (2016) 052301; Phys. Rev. D94 (2016) 034042



- HERA data prefers fluctuating substructure of the proton target

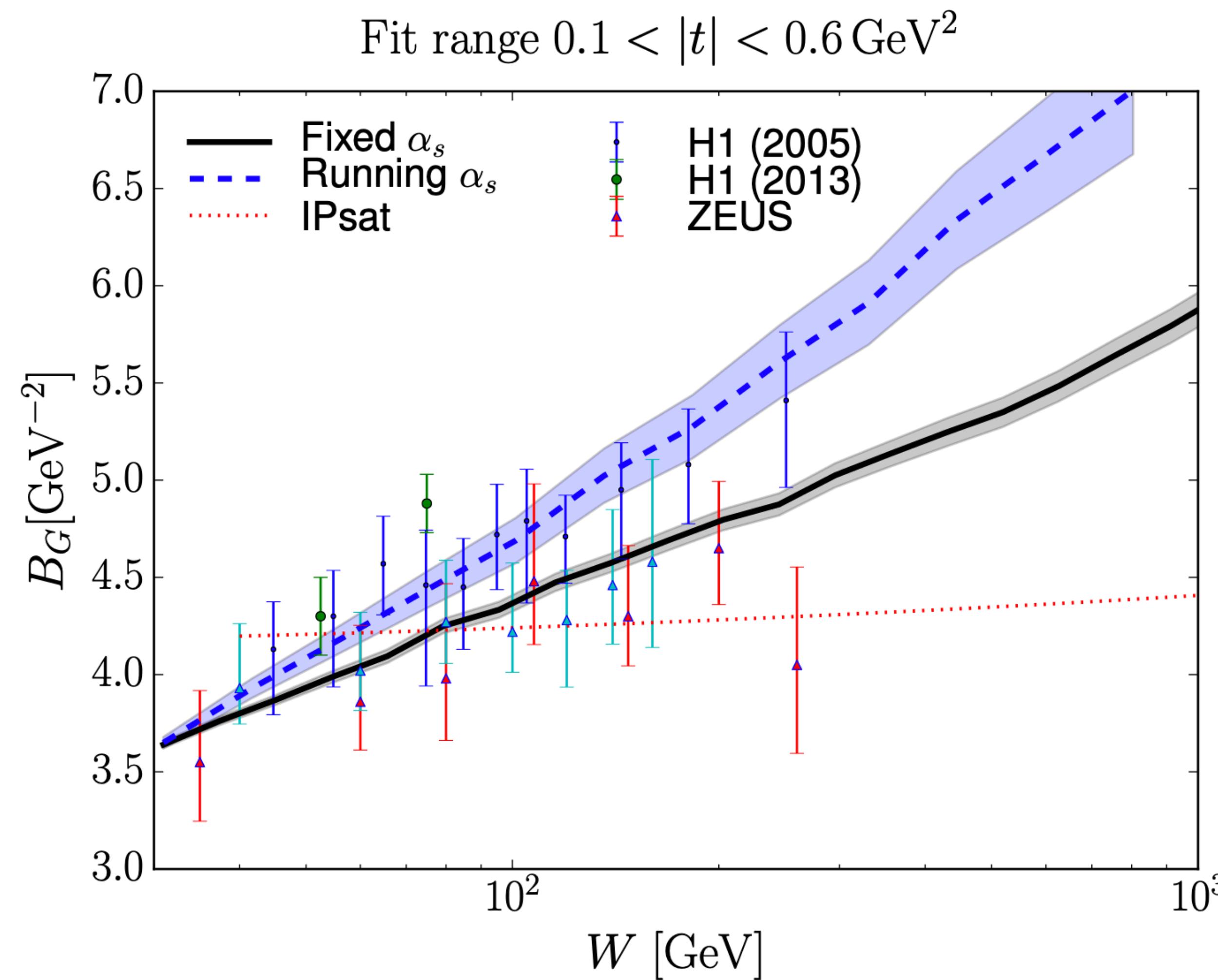
tuned shape  
fluctuations



~round proton

# Diffractive vector meson production

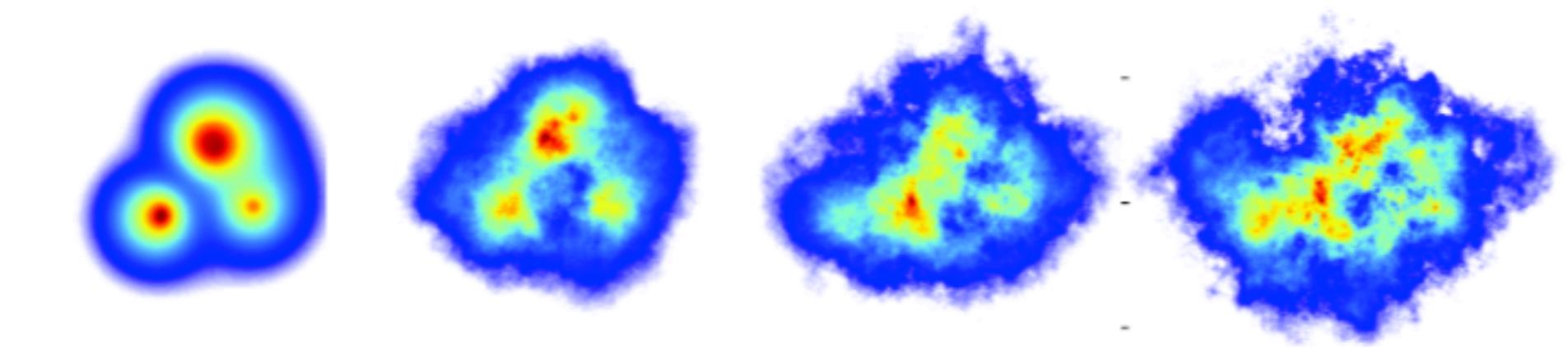
H. Mäntysaari and B. Schenke, Phys.Rev. D98 (2018) 034013



Small- $x$  evolution describes  
energy evolution of the  
proton size

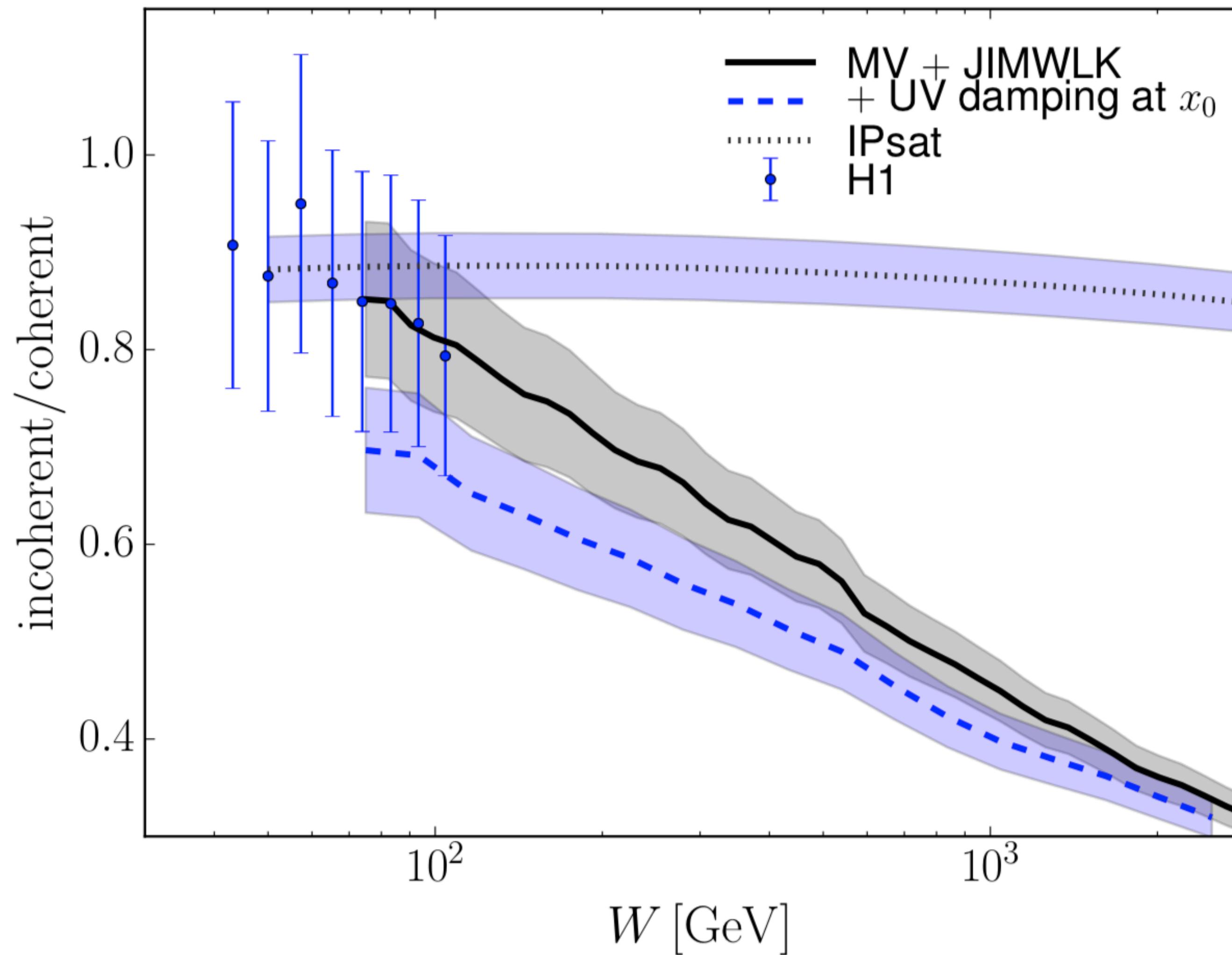
Diffractive slope shown

$W=75 \text{ GeV}$  ——————  $W=680 \text{ GeV}$



# Diffractive vector meson production

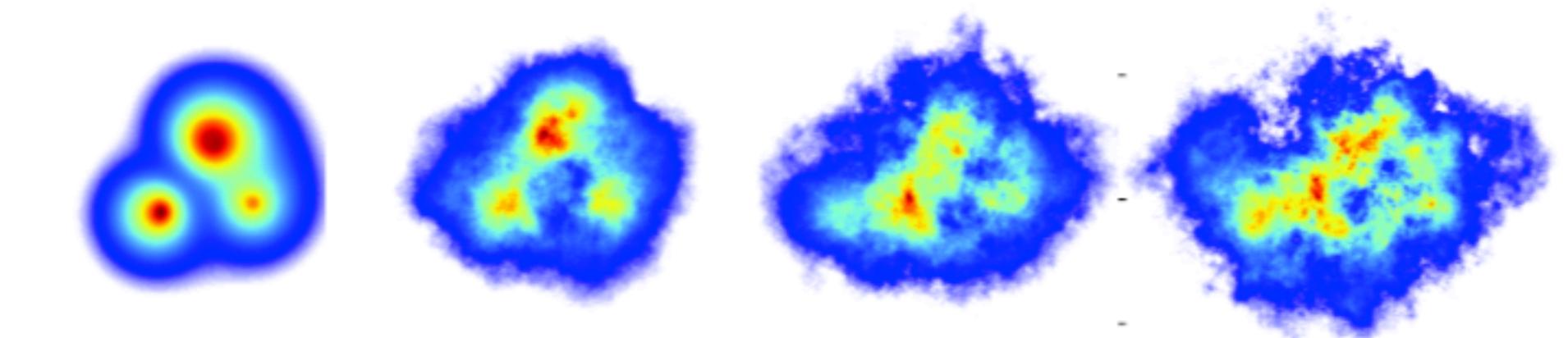
H. Mäntysaari and B. Schenke, Phys.Rev. D98 (2018) 034013



Small- $x$  evolution describes  
energy evolution of the  
proton shape and  
fluctuations & change in  $Q_s$

Cross section ratio  
compatible with H1 data

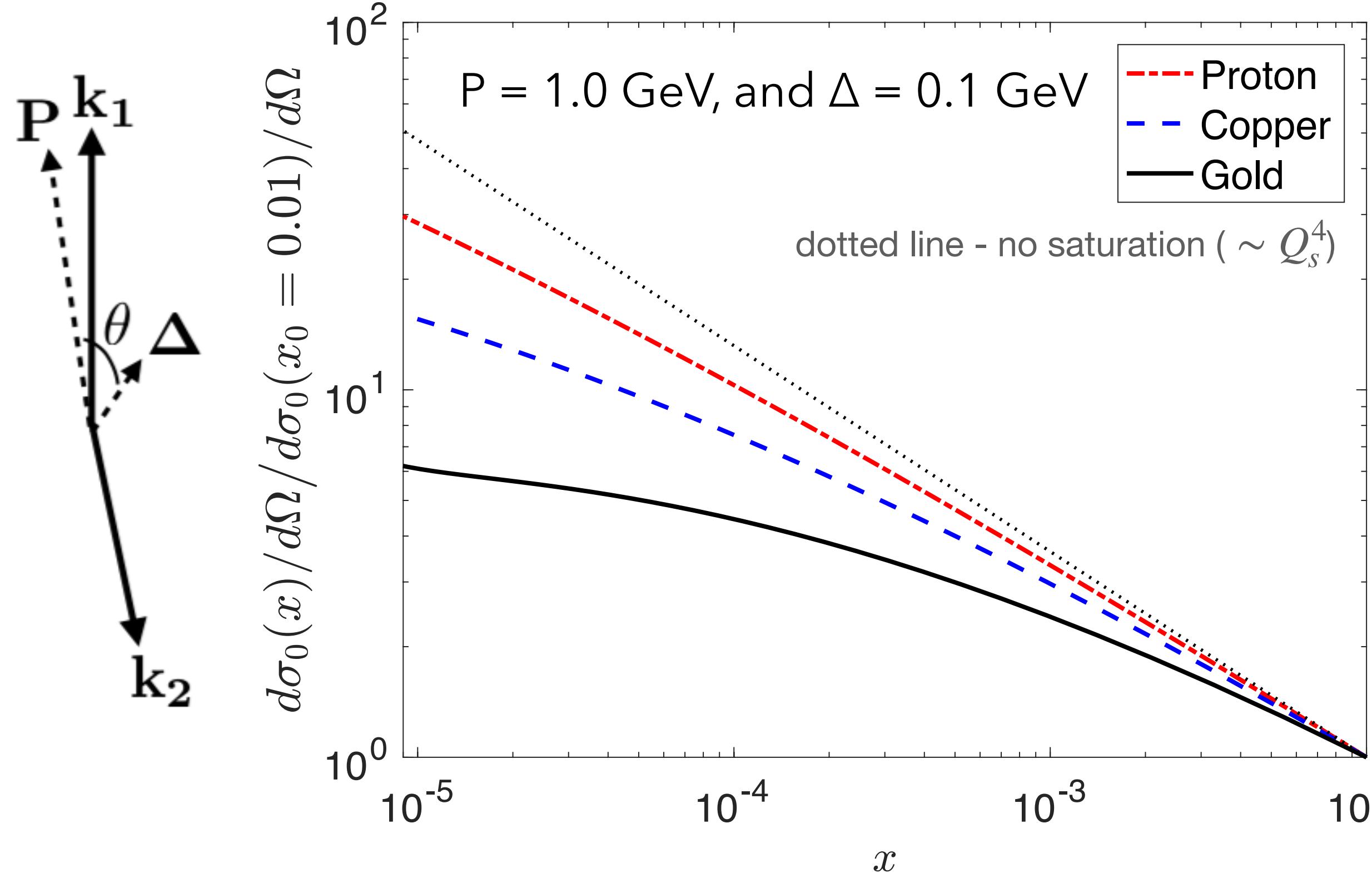
$W=75 \text{ GeV} \longrightarrow W=680 \text{ GeV}$



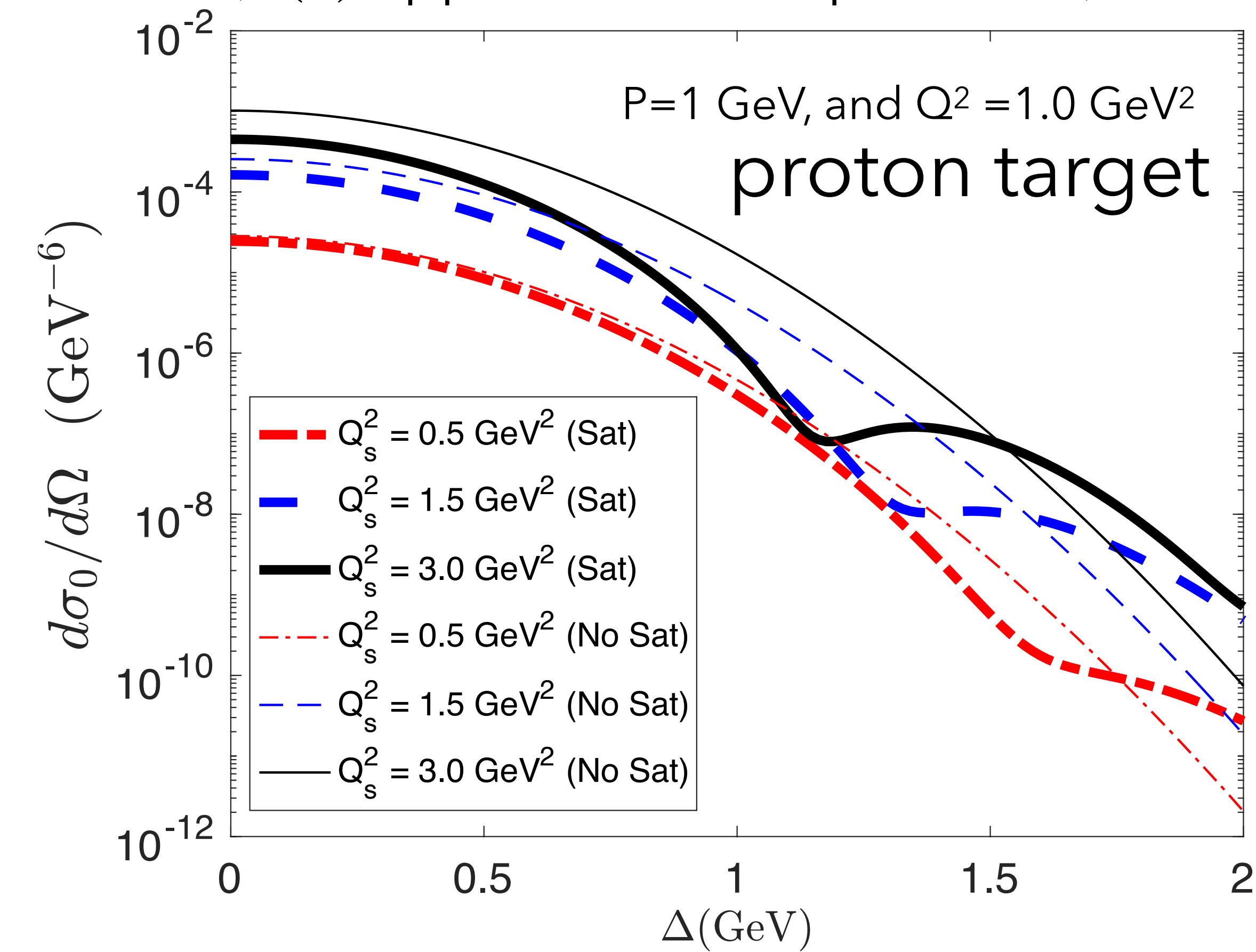
# Diffractive dijet production - saturation effects

F. Salazar, B. Schenke, Phys.Rev. D100 (2019) 034007

Slow-down of growth of  
the cross section for heavy nuclei



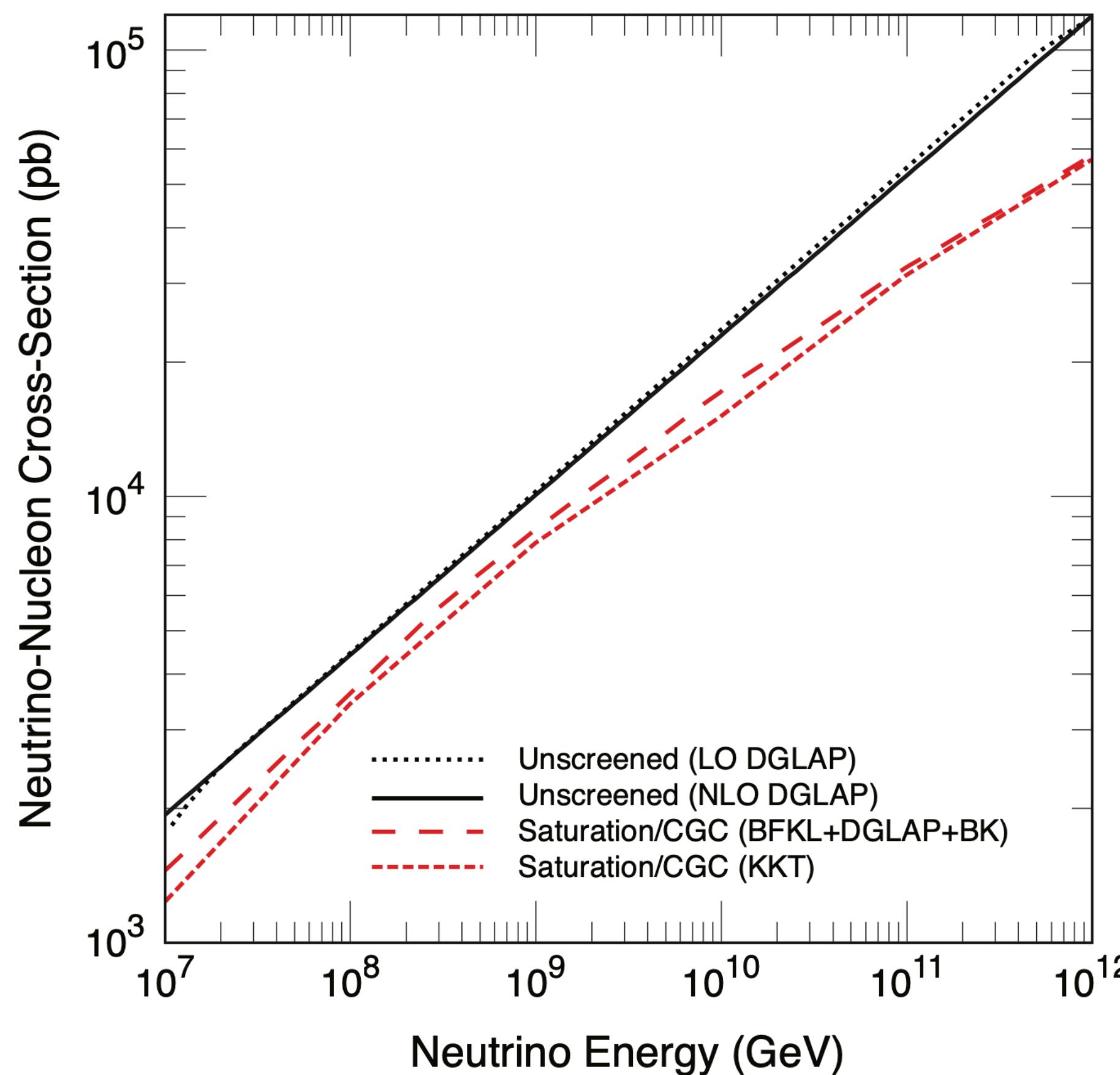
Saturation leads to diffractive dip  
even for a Gaussian proton  
( $T(b)$  appears in the exponential)



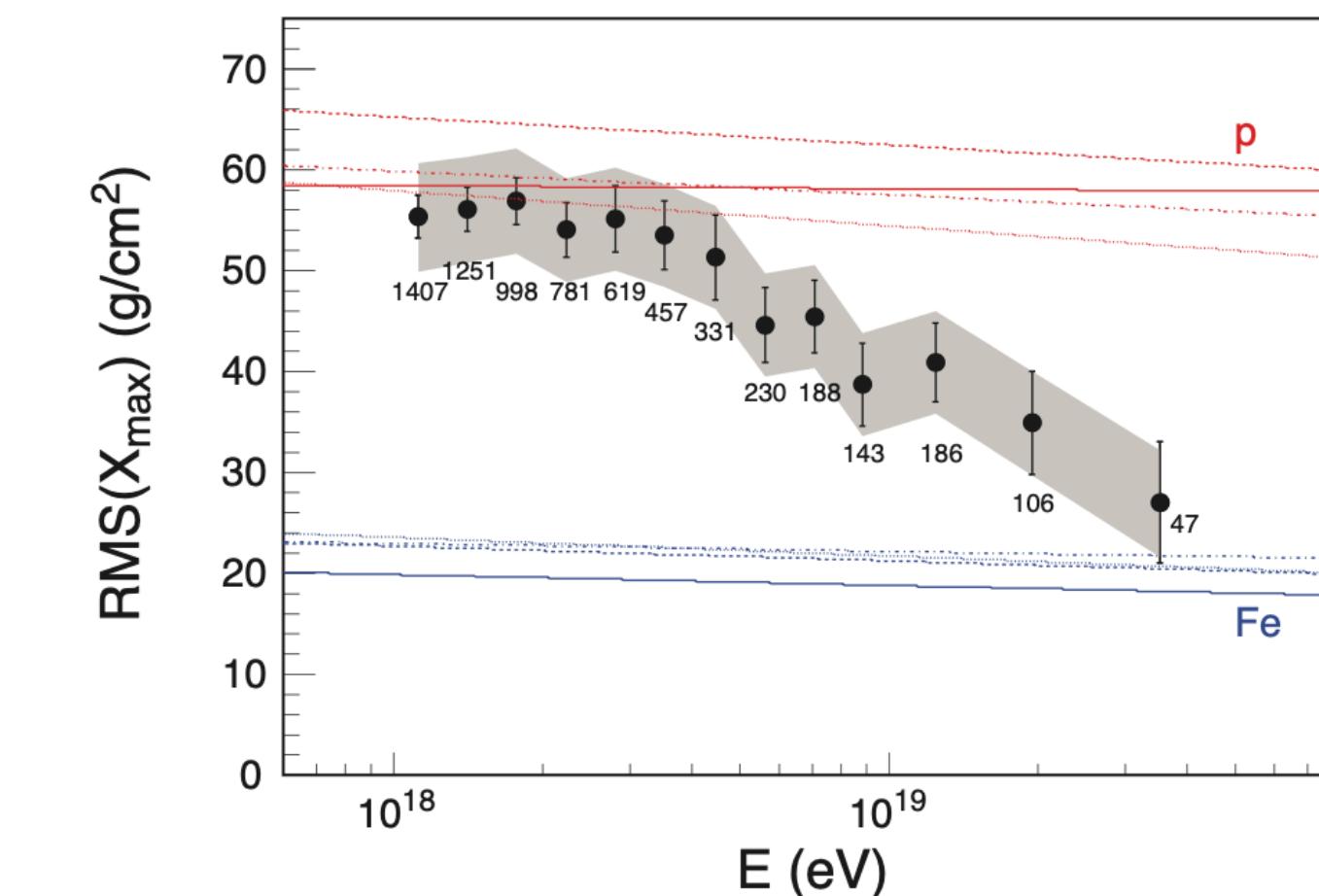
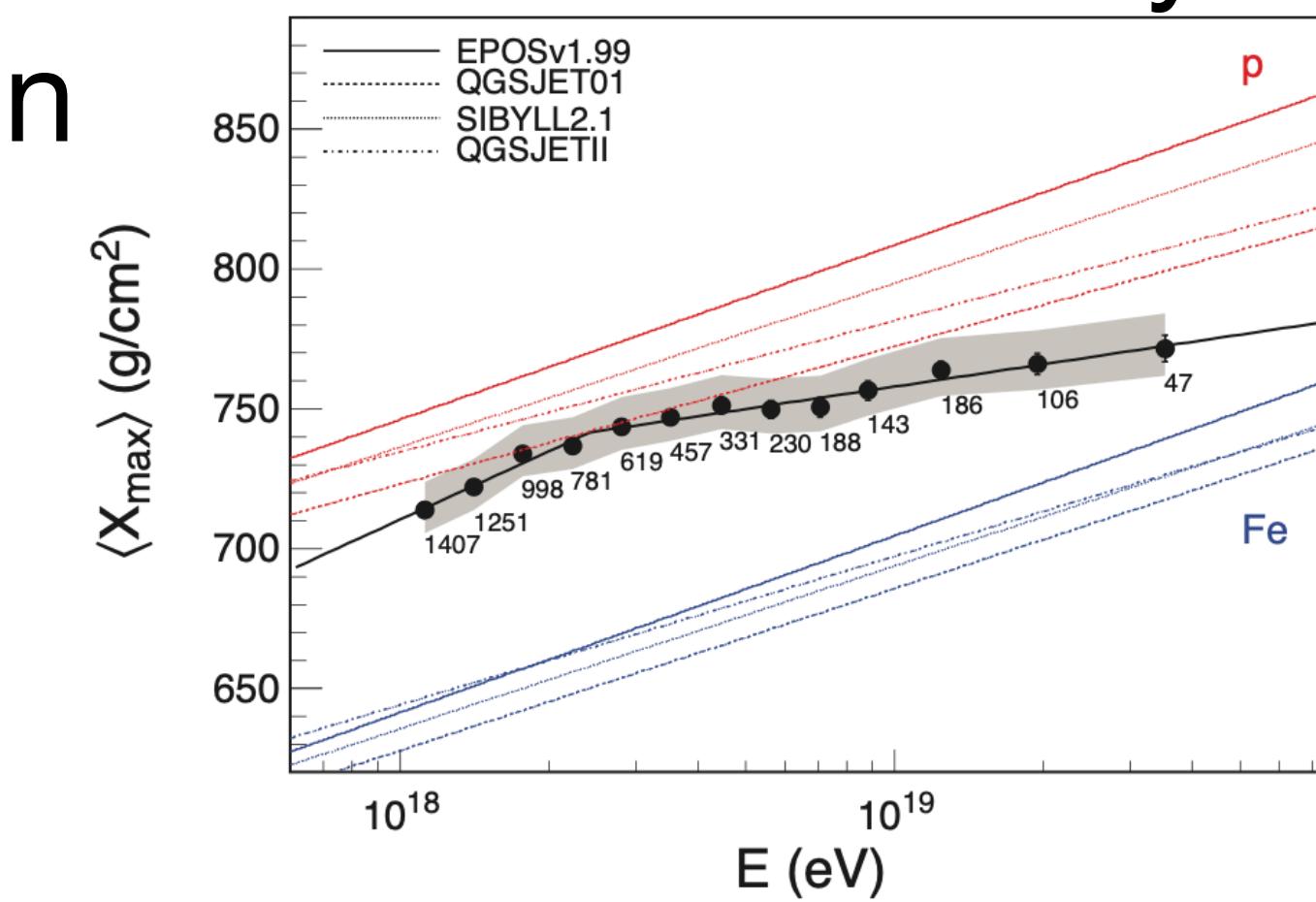
# Cosmic ray physics

Saturation can play an important role for cosmic rays

Neutrino-nucleon cross section depends on saturation effects:



Interaction depth of cosmic ray showers could be affected by saturation



# Theory developments

Calculations within the color glass condensate are moving to NLO:

NLO Impact factors for

- Fully inclusive DIS Balitsky, Chirilli; Beuf; Hänninen, Lappi, Paatelainen
- Semi inclusive single particle production in p+A  
Chirilli, Xiao, Yuan; Altinoluk, Armesto, Beuf, Kovner, Lublinsky;  
Hänninen, Lappi, Paatelainen
- Photon+dijet production in e+A Roy, Venugopalan
- Exclusive light vector meson and dijet production  
Boussarie, Grabovsky, Ivanov, Szymanowski, Wallon

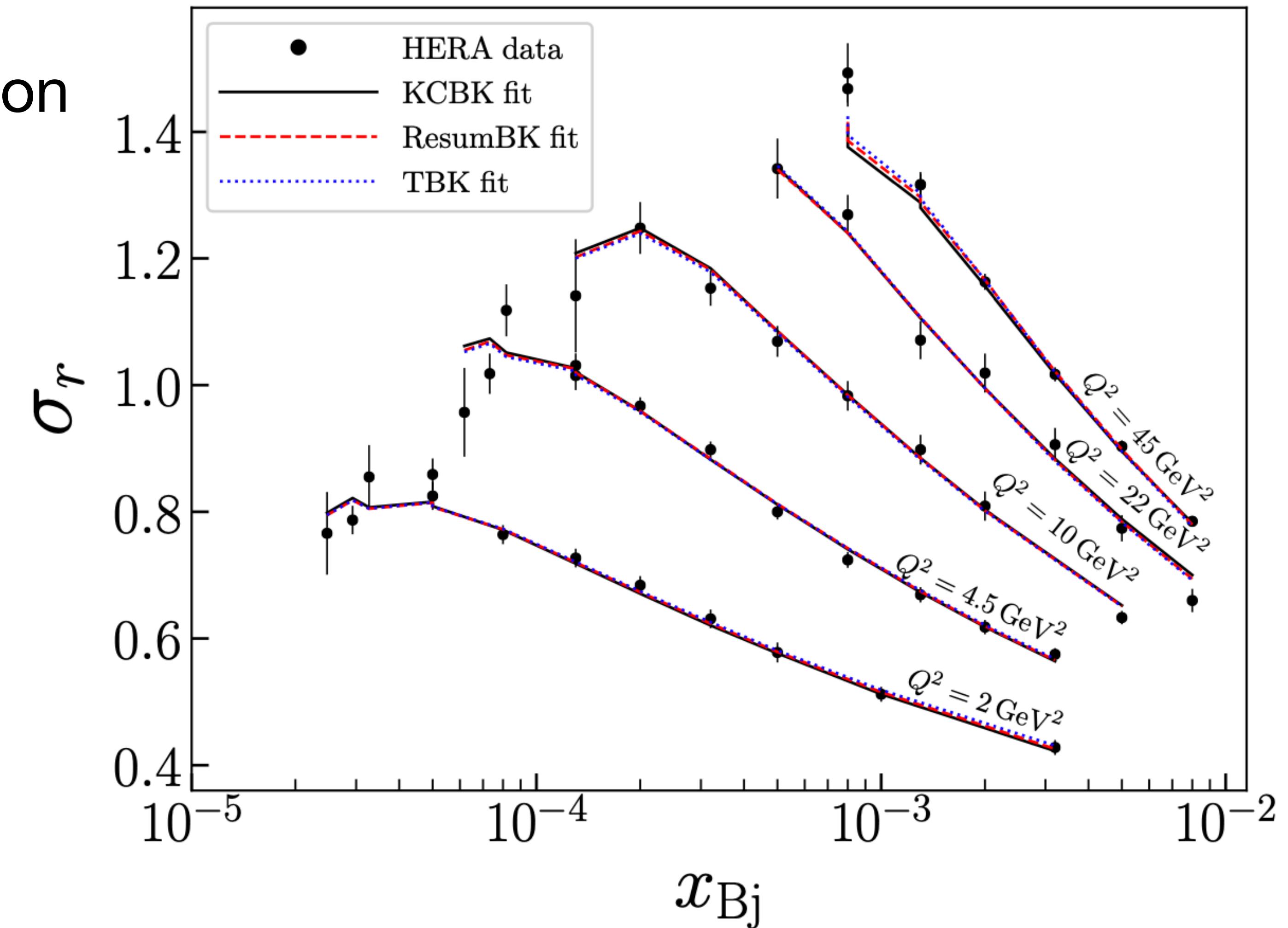
NLO evolution equations

- NLL Wilson line evolution Balitsky, Chirilli
- NLL dipole evolution Balitsky, Chirilli
- NLL 3-point operator evolution Balitsky, Grabovsky
- NLL 4-point operator evolution Grabovsky
- NLL JIMWLK Hamiltonian (from 4 above results) Kovner, Lublinsky, Mulian

# Theory developments

First numerical solutions of the Balitsky-Kovchegov (BK) evolution at NLO are becoming available.  
Can be implemented in fits to HERA structure function data

G. Beuf, H. Hänninen, T. Lappi, H. Mäntysaari  
arXiv:2007.01645



# Overlap and synergy with other LOIs

EIC Letter of Interest: Higher twist effects in inclusive and diffractive nuclear structure functions

K. Golec-Biernat, L. Motyka, M. Sadzikowski, and W. Si?ominski SNOWMASS21-EF5\_EF6-076.pdf

Impact of the Electron Ion Collider on particle physics at the Energy Frontier

R. Boughezal, S.V. Chekanov, I. Cloet, T. Hobbs, J.R. Love, F.J. Petriello, D. Wiegand, R. Yoshida SNOWMASS21-EF4\_EF6\_EF7\_TF7\_chekanov-034.pdf

Parton density functions, multi-quarks states, precision measurements and searches for signatures beyond the Standard Model using the Standard Model Effective Field Theory

Small-x parton physics on lattice

Xiangdong Ji, Luchang Jin, Bo-Wen Xiao and Feng Yuan SNOWMASS21-EF6\_EF0-TF5\_TF2-165.pdf

Particle production and correlations in dilute-dense collisions in the CGC framework: finite-width target effects

Pedro Agostini, Tolga Altinoluk, and Nestor Armesto SNOWMASS21-EF6\_EF5\_Altinoluk-270.pdf

# Overlap and synergy with other LOIs

PDFs,  $\alpha_s$  and Low-x Physics at Future DIS Facilities

LHeC/FCC-eh: Future (energy frontier) Electron-Proton and Electron-Hadron Colliders

The LHeC/FCC-eh PDF & Low x Study Group [SNOWMASS21-EF6\\_EF5\\_Armesto\\_LHeC\\_PDFs-174.pdf](#)

Jet Physics at the Electron Ion Collider

The EICjets Community [SNOWMASS21-EF6\\_EF7-TF2\\_TF6-CompF3\\_CompF2-153.pdf](#)

Heavy Flavors at the EIC

H. Abdolmaleki (IPM) et al. [SNOWMASS21-EF6\\_EF7-TF2\\_TF7-CompF2\\_CompF0\\_Ivan\\_Vitev-068.pdf](#)

Hadronic Tomography at the EIC and the Energy Frontier

S. Fazio et al. [SNOWMASS21-EF6\\_EF7-TF5\\_TF7-CompF2\\_CompF3\\_Hobbs-205.pdf](#)

LHeC and FCC-eh: Small-x Physics at Energy Frontier  
Electron-Proton and Electron-Nucleus Colliders

N. Armesto et al. [SNOWMASS21-EF6\\_EF7\\_Armesto\\_LHeC\\_Smallx-175.pdf](#)

Jet quenching and gluon saturation

Krzysztof Kutak, Wieslaw Placzek, Martin Rohrmoser <sup>34</sup> [SNOWMASS21-EF7-026.pdf](#)

# Summary

- The EIC is expected to start operation in 2030 and the experimental identification and study of gluon saturation is one of its major science goals
- Gluon saturation becomes increasingly important also for particle production in hadronic collisions as the collision energy increases
- Theory is advancing significantly, moving on to NLO calculations
- A series of observables has been identified and predictions are improving
- Detailed studies for detector requirements in the ongoing EIC Yellow Report
- A very active and exciting field